Bai *et al. Energy Informatics* (2024) 7:83
https://doi.org/10.1186/s42162-024-00403-6

Energy Informatics

RESEARCH **Open Access**

Carbon emission accounting and decarbonization strategies in museum industry

Yan Bai[1], Xiaohong Yang[2], Lan Zhang[1*], Rui Zhang[1], Nan Chen[2] and Xiaojuan Dai[2]

*Correspondence:
zhanglan_92@163.com

[1] China National Institute of Standardization, Beijing 100191, China
[2] National Museum of China, Beijing 100006, China

Abstract

Carbon peaking and achieving carbon neutrality have emerged as pivotal strategic imperatives in China. These objectives not only drive a shift in production, lifestyle, and consumption patterns but also illuminate a path towards a comprehensive green metamorphosis in China's economic and social development landscape. The distinctive nature of museums as quintessential public edifices, requiring sustained regulation of temperature and humidity alongside attracting substantial foot traffic, positions them as crucial pioneers in the pursuit of carbon peaking and neutrality. It is essential for museums to leverage their leadership and advocacy roles to catalyze low-carbon construction practices across society. This study delves into the energy dynamics specific to the museum sector, delving into the recycling of exhibition materials, methodologies for carbon footprint assessments of visitors and museum staff, and the establishment of a standardized carbon emission accounting framework tailored to the museum industry. Through meticulous examination of representative cases and subsequent analysis, this research delineates decarbonization strategies, offering indispensable technical scaffolding for carbon assessment and emission reduction efforts within the museum realm.

Keywords: Museum, Carbon accounting, Decarbonization strategies, Exhibition design, Travel patterns, Waste management

Introduction

Carbon emission accounting serves as a fundamental prerequisite for effectively undertaking carbon reduction initiatives and catalyzing the transition towards a greener economy. It stands as a vital pillar in actively engaging in international climate negotiations to combat climate change. Through quantifying carbon emissions data directly and analyzing emissions across various sectors, carbon accounting not only facilitates the identification of decarbonization pathways but also plays a pivotal role in achieving carbon neutrality goals and in the operation of carbon trading markets.

Museums serve as repositories, exhibition spaces, and research hubs for tangible artifacts representing natural and human cultural heritage, offering the public access to educational, entertaining, and learning experiences. In 2022, China saw the establishment of

322 newly registered museums, bringing the total nationwide to 6565 officially recorded museums. This equates to approximately one museum for every 220,000 individuals. Throughout the year, these museums hosted 34,000 offline exhibitions, nearly 230,000 educational activities, and welcomed a total of 578 million visitors. Concurrently, the National Cultural Heritage Administration launched nearly 10,000 online exhibitions, over 40,000 educational events, with online visits nearing 1 billion and new media engagement surpassing a million people. The majority of existing museums are outfitted with exhibition halls that necessitate constant temperature and humidity control, and they are known for their high energy consumption and notable carbon emissions, making them key targets for emission reduction initiatives among public buildings. Moreover, as representative sites of low-frequency long-distance public destinations, museums have recently witnessed a surge in both travel-related carbon emissions and their corresponding decarbonization potential. Against this backdrop, it is imperative to allocate increased attention to the carbon footprint associated with museum-related travel emissions.

This article concentrates on the museum sector, examining how to efficiently conduct carbon emissions accounting and establish corresponding decarbonization paths within the industry. It aims to address the sector's lack of accounting for other indirect carbon emissions and the unclear decarbonization pathways. The paper constructs formulas for direct and indirect carbon emissions accounting for museums, collects data on energy consumption including electricity, natural gas, gasoline, district heating, and water usage, and analyzes these data to understand the carbon emission structure of museums. Based on this analysis, carbon reduction strategies are proposed to provide a reference for the museum industry to achieve its dual carbon goals.

Research status in China and internationally

Museums, as important venues for cultural dissemination, are deeply concerned with sustainable development goals and are striving to become active participants in the cause of sustainability (Song and An 2012; Shi 2019; An 2021). In 2018, the International Council of Museums (ICOM) established a working group on museums and sustainability, calling for museums to integrate sustainability into all aspects of their operations, making it a part of their thinking and daily work (An 2021). In 2022, ICOM officially published a new definition of museums, clearly stating that museums should promote diversity and sustainability. This year, the theme of International Museum Day, "Museums, Sustainability, and Well-being", further emphasizes the important role that museums will play in supporting climate action and promoting sustainable development. As mentioned in reference (Wang and Song 2022), museums have both the responsibility and the ability to speak out in the field of sustainable environments. In China, various types of museums are actively integrating the concept of ecological civilization with their own characteristics to implement the idea of sustainable development. For example, some natural history museums and geological museums leverage their professional specialties to fully utilize their basic exhibitions, science education, and public promotion activities to play a positive foundational role in promoting the construction of an ecological civilization, practicing green development, and disseminating the concept of sustainable development (Shi 2015; Li et al. 2021; Zhao 2019). References (Cai and Wang

2017) to Yang et al. (2023) also provide examples of methods, technologies, and cases of energy conservation and reduction, green low-carbon practices from the perspectives of architectural design, technical energy conservation, and energy management systems.

In the realm of carbon accounting in the construction sector, in 2015, the National Development and Reform Commission (NDRC) issued guidelines for greenhouse gas accounting methods and reports across ten industries. Among them was the *Guidelines for Greenhouse Gas Emission Accounting for Public Building Operation Units (Enterprises) (Trial)*, which established emission accounting methods for operating units such as office buildings, commercial buildings, tourist facilities, and educational and healthcare structures during their operational phases. The guidelines encompass emissions from both stationary and mobile combustion sources, emissions from purchased electricity and heat, and utilize emission factors to determine greenhouse gas accounting methods. In 2019, the Ministry of Housing and Urban–Rural Development (MOHURD) released the national standard *GB/T 51366 Building Carbon Emission Calculation Standard*, outlining the calculation of carbon emissions during the operation, construction, demolition phases of buildings, as well as during the production and transportation of building materials. Furthermore, the commonly employed methods for carbon emissions measurement and accounting primarily include five approaches: direct measurement (Gao et al. 2021; Tang and Zhang 2022; Zhao et al. 2013), material balance algorithm (Zhang et al. 2019a), emission factor method (IPCC 2006), life cycle assessment (Zhang et al. 2019b), and input–output analysis (National Bureau of Statistics 2000). Given that public building carbon emissions predominantly focus on both direct and indirect emissions, with readily accessible activity data and standardized default emission factors, the carbon emission accounting during the operational phase of public institutions often employs the emission factor method.

In the realm of research into decarbonization pathways, international studies on carbon emissions in the construction sector trace back to the LMDI factor decomposition method from 1998. This method is primarily utilized for data categorization and has been widely applied in analyses of carbon emission influencing factors and their respective weights. Subsequently, researchers such as Ang et al. have employed the LMDI method to study basic energy data in Singapore, China, and South Korea (Ang et al. 1998). Battisti and his colleagues discovered that the use of clean energy sources like solar systems can effectively mitigate carbon emissions during the operational phase of buildings (Battisti and Corrado 2005). Moving into the twenty-first century, several European Union nations have successively developed advanced energy-saving technologies and corresponding policies. Building upon these innovative building energy monitoring technologies, they have pioneered energy management platforms (Doukas et al. 2007; Bartone et al. 2003; Alahmad et al. 2011). Additionally, scholars like Wang suggest that the application of energy-saving technologies such as greening with vegetation, utilization of new energy sources, building equipment enhancements, and efficient post-construction management can propel the emission reduction efforts in green buildings (Wang 2022). Cheng and others advocate for precision design, prefabricated construction, and intelligent operations (Cheng 2022). By implementing measures such as scientific design, material management control, eco-friendly construction, and intelligent operational maintenance, they aim to enhance energy efficiency levels in buildings and guide the quality improvement and optimization of green building development. Furthermore, Yang and colleagues have integrated meteorological conditions, building operational status, human energy consumption patterns, and applied data mining algorithms to achieve functions like data quality assessment, energy consumption prediction, and anomaly alerts (Yang et al. 2015). These extended functionalities provide a theoretical basis for energy management practices.

When it comes to carbon accounting for museums, as exemplary public buildings, museums, based on their functional characteristics, also encompass issues related to indirect emissions such as travel and consumables. The museum industry involves employee commuting, visitor travel, exhibition materials, kitchen waste from staff dining, and visitor waste disposal, among other factors. However, research focusing on these aspects is relatively scarce. In terms of decarbonization pathways, there has been substantial research on energy restructuring and energy-saving renovations. Nevertheless, there is a lack of in-depth analysis on decarbonization pathways specific to the museum industry, highlighting the pressing need for targeted research in this area.

Museum carbon emission accounting model

Scope of accounting

The scope discussed herein pertains to the carbon emissions generated by museums during their operational processes. Emissions from fossil fuel combustion encompass carbon dioxide emissions generated during the combustion of fuels such as coal, natural gas, gasoline, and diesel. Emissions from purchased and consumed electricity and heat include the carbon dioxide emissions produced during the generation of purchased electricity and heat (steam, hot water) in the corresponding production processes. Other indirect emissions encompass materials, which refer to emissions generated by materials used during museum operations; transportation, which includes the carbon dioxide emissions generated by museum staff commuting using private vehicles or public transportation, as well as emissions from visitors traveling to the museum during its operational hours; and household waste, which includes the carbon dioxide emissions from waste disposal by visitors and staff during museum operations.

Accounting steps and methods

Within the accounting process, the workflow includes delineating the accounting boundaries, identifying sources of carbon dioxide emissions, collecting activity data, selecting and acquiring emission factor data, calculating the emissions from fossil fuel combustion, purchased and consumed electricity and heat, and other generated carbon dioxide emissions separately, and summarizing the total carbon dioxide emissions.

The total carbon dioxide emissions of a museum equal the sum of all emissions within the accounting boundaries, including emissions from fossil fuel combustion, purchased and consumed electricity and heat, and other indirect carbon dioxide emissions, while subtracting the carbon dioxide emissions corresponding to the consumed electricity and heat outputs, calculated according to formula (1).

$$E = E_{fuel} + E_{purchased\ electricity} + E_{purchased\ heat} + E_{other} - E_{output\ electricity} - E_{output\ heat} \tag{1}$$

where: E: Total carbon dioxide emissions in metric tons (tCO_2); E_{fuel}: Carbon dioxide emissions from fossil fuel combustion in metric tons (tCO_2); $E_{\text{purchased electricity}}$: Carbon dioxide emissions from purchased electricity in metric tons (tCO_2); $E_{\text{purchased heat}}$: Carbon dioxide emissions from purchased heat in metric tons (tCO_2); E_{other}: Other indirect carbon dioxide emissions in metric tons (tCO_2); $E_{\text{output electricity}}$: Carbon dioxide emissions from electricity output in metric tons (tCO_2); $E_{\text{output heat}}$: Carbon dioxide emissions from heat output in metric tons (tCO_2).

Due to the emissions from fossil fuel combustion, and the emissions generated by purchased and consumed electricity and heat, the accounting formulas can be referenced in the *Guidelines for Greenhouse Gas Emission Accounting and Reporting for Public Building Operation Units (Enterprises)* document. This study focuses primarily on studying the formulas for the three categories of other indirect emissions: materials, transportation, and waste.

Emissions from exhibition materials

The carbon emissions associated with exhibition materials at the museum encompass the carbon emissions generated during the material production and transportation phases, calculated according to formula (2). The carbon emission factors for the material production phase should preferably be based on third-party verified material carbon footprint data. In the case of exhibition materials being reusable, the carbon emissions from the material production phase are only considered during the initial use.

$$C_{cl} = C_{sc} + C_{ys} \tag{2}$$

where: C_{sc}: Carbon dioxide emissions during the material production phase ($kgCO_2$); C_{ys}: Carbon dioxide emissions during the material transportation phase ($kgCO_2$).

The carbon emissions during the material production phase and material transportation phase can be calculated using formulas (3) and (4) respectively.

$$C_{sc} = \sum_{i=1}^{n} M_i F_i \tag{3}$$

where: M_i: Consumption of the i-th material; F_i: Carbon emission factor for the i-th material ($kgCO_2/m^3$ or $kgCO_2/kg$).

$$C_{\text{ys}} = \sum_{i=1}^{n} M_i D_i T_i \tag{4}$$

where:

D_i: Average transport distance for the i-th material (km); T_i: Carbon emission factor for the unit weight transport distance of the ith material [$kgCO_2/(t \cdot km)$].

Emissions from transportation

The carbon dioxide emissions from different modes of transportation are calculated using formula (5).

$$PE_y = \sum\nolimits_i \sum\nolimits_k (EF_{PKM,k} \times PD_{i,k,y}) \tag{5}$$

where: PE_y: Carbon emissions from transportation modes in the y-th year, measured in kilograms of carbon dioxide (kgCO_2); k: Mode of transportation, which can include private cars, railways, public transport, taxis, cycling, airplanes, etc.; $EF_{PKM,k}$:Carbon emission factor per person-kilometer for the transportation mode k in the base year, measured in kilograms of CO_2 per person-kilometer (kgCO_2/PKM). Default values for carbon emission factors for different modes of transportation can be referenced; $PD_{i,k,y}$: Distance travelled in kilometers (km) using transportation mode k for the i-th time in the y-th year.

Emissions from household waste produced by museums

The carbon dioxide emissions generated from disposing of household waste are calculated using formula (6).

$$C_{ij} = \sum_{i=1}^{n} M_{lji} \times EF_{lji} \tag{6}$$

where: C_{lj}: Carbon emissions from disposing of household waste, measured in kilograms of carbon dioxide (kgCO_2); i: Type of household waste disposed of; EF_{lji}: Mass of the i-th type of household waste, measured in tons (t); EF_{lji}: Carbon emission factor corresponding to the i-th type of household waste, measured in kilograms of CO_2 per ton (kgCO_2/t).

Data sources and limitations

The museum carbon emission accounting model takes into account several key factors. Firstly, the data sources include energy consumption (such as electricity, gas, and oil), which are collected through metering devices and purchase records (ledgers/invoices); data on exhibition materials are also obtained through purchase records; transportation data relies on commuting ledgers and ticket reservation management systems; and data on domestic waste come from waste management ledgers.

In terms of assumptions, the model relies on standard emission factors to estimate the carbon emissions of various energy sources and activities, and it is assumed that all necessary data are accessible.

However, the model has certain limitations. Data incompleteness is an issue because some data may be difficult to obtain, and in such cases, estimates may need to be made using averages, which can lead to certain errors. Moreover, standard emission factors may not be fully applicable in all situations, which could affect the accuracy of the estimates. Finally, due to the model's simplification, it cannot fully reflect all details, which may also result in simplification errors.

In summary, the museum carbon emission accounting model is a complex system that requires careful consideration of data sources, assumptions, and limitations to ensure the accuracy and reliability of the estimation results.

Carbon accounting and decarbonization pathway analysis

Carbon accounting illustration of the National Museum

The Chinese National Museum is a grand repository of historical and cultural treasures, showcasing the rich tapestry of traditional Chinese culture, revolutionary ideals, and progressive socialist values. The museum covers an area of 200,000 square meters and contains over 1.4 million exhibits, spread across 48 exhibition halls. It also offers public leisure areas and features an underground parking lot that can accommodate nearly 600 vehicles. In the past ten years, the museum has received an average of about 6 million visitors each year.

Diverse energy resources sustain the museum's operations, including electricity, natural gas, gasoline, district heating, and water. Electricity powers essential functions such as air conditioning, illumination, and machinery. Heating resources are primarily dedicated to winter warmth, while natural gas fuels steam humidification boilers and supports the culinary operations in the canteen. For the year 2023 (as illustrated in Fig. 1), electricity, heating, and natural gas prominently feature as the primary sources of energy consumption, collectively constituting a substantial 99.63% of the total energy usage, while gasoline accounts for a minor 0.37%. Among energy expenditure categories, electricity expenses claim the largest share at 72.1%, followed by heating costs at around 21.8%, and natural gas expenditures approximately at 5.5%.

Utilizing the carbon accounting methodology and employing formulas for direct and indirect emissions generated by electricity and heating, the total carbon dioxide emissions trend within the accounting boundary from 2016 to 2023 exhibits a relatively stable pattern with some fluctuations. Figure 2 illustrates the continuous trend of carbon dioxide emissions over eight years, with 2016 serving as the benchmark year. From Fig. 2a), it is evident that the total carbon emissions peaked in 2018, with a notable decline observed between 2018 and 2020. This substantial decrease can be attributed to the impact of the COVID-19 pandemic, which resulted in a reduced influence of visitor numbers on energy consumption, consequently leading to a decrease in carbon dioxide emissions. Examining Fig. 2b), the fluctuation of indirect carbon emissions stemming from heating generation remains relatively stable, whereas indirect carbon emissions from electricity generation exhibit a two-phase trend. The period from 2016 to 2019 marks the first phase characterized by a gradual yearly increase in indirect carbon

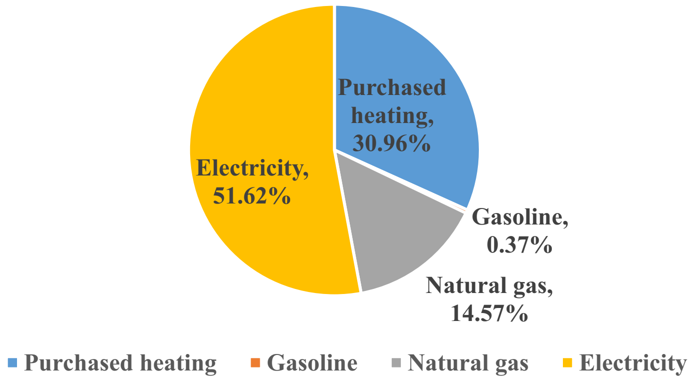

Fig. 1 Distribution of energy consumption structure

a Trend in total carbon emissions from 2016 to 2023

b Comparison of indirect carbon emissions from 2016 to 2023

Fig. 2 **a** Trend in total carbon emissions from 2016 to 2023. **b** Comparison of indirect carbon emissions from 2016 to 2023

emissions from electricity generation. Subsequently, the period from 2020 to 2023 represents the second phase, where indirect carbon emissions from electricity generation initially decreased to a certain level in 2020 before resuming an upward trajectory in the following years. Both phases, influenced by the COVID-19 pandemic, showcase a yearly increase in indirect carbon emissions from electricity generation, primarily attributed to the rise in electricity consumption for exhibitions. As museums strive to weave compelling narratives behind cultural artifacts, the increasing emphasis on utilizing information technology in exhibitions has led to a gradual rise in electricity consumption over the years.

Utilizing the carbon accounting method based on formulas for carbon emissions from waste disposal, consumption of exhibition materials and paints, as well as carbon emissions generated from visitors and staff travel, the carbon emission proportions of various categories in the museum in 2023 are depicted in Fig. 3 (carbon emissions from waste classification are less than 0.1% and are not included). From Fig. 3, it is evident that other indirect carbon emissions constitute approximately 31% of the total, with exhibition board materials accounting for 1%, decorative paints for 1%, and travel contributing a significant 29%. As a crucial gateway for promoting national and civilizational achievements, the museum attracts a growing number of visitors for educational and cultural explorations, resulting in notably high carbon emissions from travel. Specifically regarding travel-related carbon emissions, subway travel constitutes 18%, bus travel 10%, and employee commuting by car 1%. Positioned to the east of Tian'anmen Square and adjacent to Tian'anmen East Station on Metro Line 1, the National Museum of China benefits from convenient subway transportation options, prompting a majority of visitors to opt for subway travel when visiting the museum. Consequently, subway travel accounts for a substantial proportion of travel-related carbon emissions.

Data uncertainty analysis and data quality management

Data uncertainty analysis

The uncertainty of direct emissions is determined by the uncertainty of direct emissions from natural gas, liquefied petroleum gas, and gasoline. The direct emissions of carbon dioxide are calculated using the emission factor method, and the influencing factors of the uncertainty of direct emissions include two aspects: the uncertainty

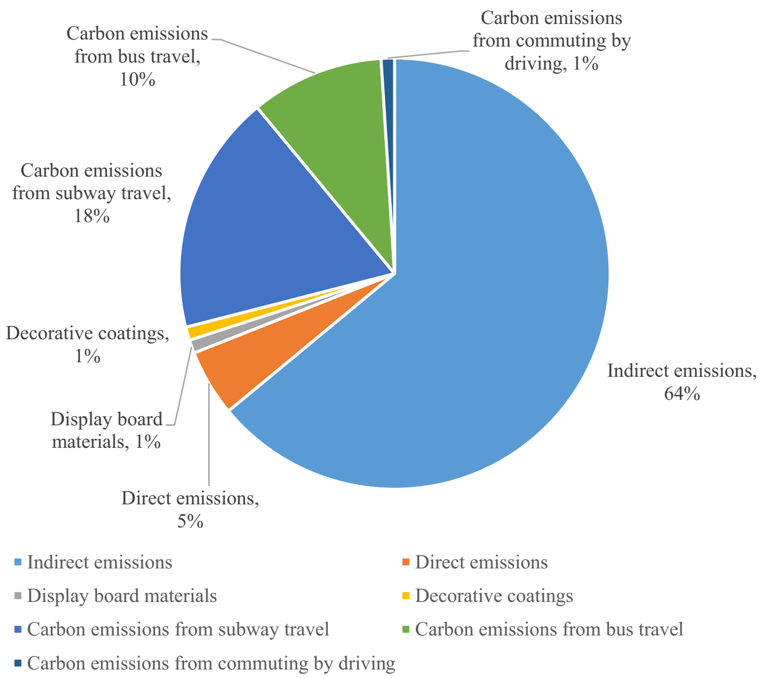

Fig. 3 Proportions of various carbon emissions categories. The carbon emission factors cited in this section are sourced from the European Plastic Database PE (2005), European Plastic Database PE, *Guidelines for Greenhouse Gas Emission Accounting and Reporting for Public Building Operating Units (Enterprises)*, *Methods for Low Carbon Travel in Beijing* (Ji.H.F (2022) No. 7, Appendix 5), Chinese Resource Science, and the 2021 Collection of Greenhouse Gas Emission Coefficients for the Entire Lifecycle of Chinese Products (2022) (Zhang et al. 2019a)

of activity level and the uncertainty of emission factor. The calculation formula for uncertainty is as follows formula (7):

$$U_c = \sqrt{U_{s1}^2 + U_{s2}^2 \cdots + U_{sn}^2} \tag{7}$$

where: Uc is the uncertainty (%) of the product of n estimated values; Us1…Usn are the uncertainties (%) of the estimated values.

The formula for calculating the comprehensive uncertainty of direct emissions is as follows formula (8):

$$U_c = \frac{\sqrt{(U_{s1} \cdot \mu_{s1})^2 + (U_{s2} \cdot \mu_{s2})^2 + \cdots (U_{sn} \cdot \mu_{sn})^2}}{|\mu_{s1} + \mu_{s2} + \cdots + \mu_{sn}|} \tag{8}$$

where: Uc is the uncertainty (%) of the sum or difference of n estimated values; μs1…μsn are the estimated values; Us1…Usn are the uncertainties (%) of the estimated values.

(1) Direct emissions uncertainty of natural gas

   (i) Uncertainty of activity level

Activity Level Uncertainty involves uncertainty in natural gas consumption and uncertainty in the lower heating value.

Natural gas consumption is measured by gas meters, and the uncertainty in consumption is determined by the accuracy of the gas meters. The main gas meters have an accuracy rating of 1.0, resulting in an average uncertainty of 1.0% in natural gas consumption. If the uncertainty in the lower heating value of natural gas is set at 5%, then the quantified result of activity level uncertainty is 5.10%. The specific calculation process is as follows formula (9):

$$U_{c1} = \sqrt{U_{s1}^2 + U_{s2}^2} = \sqrt{(1.0\%)^2 + (5\%)^2} = 5.10\% \tag{9}$$

(ii) Uncertainty of emission factor

The uncertainty of the emission factor is determined by the uncertainty of the carbon content per unit of heat value of natural gas and the carbon oxidation rate. If the uncertainty of the carbon content per unit of heat value of natural gas is 5% and the uncertainty of the carbon oxidation rate is 1%, then the quantified result of the emission factor uncertainty is 5.10%. The specific calculation process is as follows formula (10):

$$U_{c2} = \sqrt{U_{s3}^2 + U_{s4}^2} = \sqrt{(5\%)^2 + (1\%)^2} = 5.10\% \tag{10}$$

(iii) Uncertainty of direct emissions

Based on the quantified results of activity level and emission factor uncertainty, the uncertainty of direct natural gas emissions is calculated to be 7.21%. The specific calculation process is as follows formula (11):

$$U_c = \sqrt{U_{c1}^2 + U_{c2}^2} = \sqrt{(5.10\%)^2 + (5.10\%)^2} = 7.21\% \tag{11}$$

(2) Uncertainty of direct emissions of liquefied petroleum gas (LPG)

(i) Uncertainty of activity level

The uncertainty of the activity level involves uncertainty in the consumption of LPG and uncertainty in the lower heating value. The emission unit purchases LPG in bottled form. If the uncertainty in LPG consumption is 2% and the uncertainty in the lower heating value of LPG is 5%, then the quantified result of the activity level uncertainty is 5.39%. The specific calculation process is as follows formula (12):

$$U_{c1} = \sqrt{U_{s1}^2 + U_{s2}^2} = \sqrt{(2\%)^2 + (5\%)^2} = 5.39\% \tag{12}$$

(ii) Uncertainty of emission factor

The uncertainty of the emission factor is determined by the uncertainty of the carbon content per unit of heat value of liquefied petroleum gas (LPG) and the carbon oxidation rate. If the uncertainty of the carbon content per unit of heat value of LPG is 5% and the uncertainty of the carbon oxidation rate is 2%, then the quantified result of the emission factor uncertainty is 5.39%. The specific calculation process is as follows formula (13):

$$U_{c2} = \sqrt{U_{s3}^2 + U_{s4}^2} = \sqrt{(2\%)^2 + (5\%)^2} = 5.39\% \tag{13}$$

(iii) Uncertainty of direct emissions

Based on the quantified results of activity level and emission factor uncertainty, the uncertainty of direct emissions from liquefied petroleum gas is calculated to be 7.62%. The specific calculation process is as follows formula (14):

$$U_c = \sqrt{U_{c1}^2 + U_{c2}^2} = \sqrt{(5.39\%)^2 + (5.39\%)^2} = 7.62\% \tag{14}$$

Based on the results of the uncertainty analysis for direct emissions from natural gas and liquefied petroleum gas, the comprehensive uncertainty of direct emissions for the emission unit is calculated to be 7.17% (Table 1). The specific calculation process is as follows formula (15):

$$\mathrm{U_c} = \frac{\sqrt{(1218.90 \times 7.21)^2 + (6.32 \times 7.62\%)^2}}{(1218.90 + 6.32)} = 7.17\% \tag{15}$$

Data quality management

Measurement Equipment Management: Gas meters and electricity meters are installed and managed by relevant companies, with measurement accuracy in line with national standards to ensure accurate measurement of energy consumption. Organizational Structure: The Equipment Management Department is responsible for carbon emissions management, and relevant personnel possess the necessary professional capabilities. Management System Development: The “Energy and Resource Conservation Management System” has been developed and implemented, covering aspects such as energy measurement, energy-saving operations, technical transformation management, publicity and training, and file management. Data Statistical Management: The Equipment Management Department conducts monthly statistics on energy consumption, establishes accounting ledgers and archives, the Budget and Finance Department is responsible for settling energy costs and archiving receipts, and regularly submits energy consumption reports.

Analysis of carbon reduction strategies

Considering the current carbon dioxide emissions of the museum, efforts are being made to maintain normal operations without compromising comfort within the premises. Strategies include adjustments to the energy structure, increased utilization of renewable energy sources, energy-saving renovations, and carbon offset purchases. By

Table 1 Comprehensive uncertainty calculation results for direct emissions

Serial No.	Energy type	Uncertainty of activity level (%)	Uncertainty of emission factor (%)	Uncertainty of emissions (%)
1	Natural gas	5.10	5.10	7.21
2	Liquefied petroleum gas	5.39	5.39	7.62
Comprehensive uncertainty		7.17		

accelerating the transition to green and low-carbon energy utilization, enhancing the green and low-carbon standards of the buildings, leveraging the circular economy to support decarbonization initiatives, and conducting green and low-carbon demonstration campaigns, calculations suggest that carbon emissions can be stabilized and gradually reduced. This article, in line with the actual situation of the museum, proposes five carbon reduction strategies (Table 2) and elaborates on the specific details of each strategy.

Pathway 1: Promoting electrification and solar energy utilization

Advancing the use of electricity to replace fossil fuels such as liquefied petroleum gas and natural gas in the museum sector, thereby reducing direct carbon emissions, is a key strategy. This involves elevating the cleanliness of energy used for office operations, exhibitions, and daily living. Particularly crucial is the promotion of decentralized humidification equipment to replace central gas steam boilers, intensifying efforts in electrifying humidity control systems, encouraging the adoption of efficient electromagnetic stoves over liquefied petroleum gas stoves, and establishing fully electric kitchens. In parallel, exploring the potential of solar energy is essential. By identifying suitable spaces like building rooftops and facades, assessing the feasibility of solar photovoltaic power generation, and advocating for the installation of solar photovoltaic power facilities, the utilization of renewable energy can be increased, fostering optimization in the energy consumption structure.

The National Museum currently possesses nearly 10,000 square meters of available roof space, capable of accommodating a 1.5 MW photovoltaic system. It is estimated to generate an annual output of 1.0196 million kWh, with installation costs amounting to 2.1752 million RMB and annual maintenance costs ranging from 34,000 to 42,000 RMB. Calculated at a unit price of 0.5 RMB/kWh, the projected investment payback period without considering maintenance is around 4.2 years, while factoring in maintenance extends the payback period to approximately five years. The direct carbon reduction amounts to 615.84 tce. Additionally, with the transformation of select areas into fully electric kitchens, an approximate carbon reduction of 6 tce can be achieved. Consequently, through Pathway 1, a total carbon reduction of 621.84 tce can be realized.

Table 2 Museum carbon reduction strategies

Serial No.	Strategies	Goal
1	Promoting electrification and solar energy utilization	Transitioning to renewable energy sources to reduce carbon emissions
2	Enhancing the low-carbon operational standards and intensifying energy-saving refurbishments at the museum	Improving energy efficiency and reducing carbon footprint through upgrades and operational changes
3	Pathway 3: Strengthening the comprehensive utilization of exhibition resources	Maximizing the use of exhibition materials and resources to minimize waste and environmental impact
4	Pathway 4: Heightening green control and management efforts	Implementing stricter environmental controls and management practices to ensure sustainability
5	Pathway 5: Initiating green and low-carbon demonstration and promotion	Leading by example and promoting sustainable practices within the museum and to the public

In addition, the construction of digital museums allows people to visit museums without leaving their homes, which not only reduces the carbon emissions associated with travel for some visitors but also provides an opportunity for people in rural and other remote areas to access museums and learn about exhibitions. This initiative is of great significance for promoting the sustainable development of museums, enhancing their social impact, and fostering cultural exchange and dissemination. Through digital means, museums can break down geographical barriers, enabling more people to enjoy cultural resources, thereby enhancing the cultural inclusiveness and educational equity of society. At the same time, digital museums can offer a more interactive and personalized visiting experience, attracting more visitors, especially the younger generation, to participate in cultural activities.

Pathway 2: Enhancing the low-carbon operational standards and intensifying energy-saving refurbishments at the museum

Progressing towards green building benchmarking management, operations and maintenance practices are fortified based on the *Technical Specification for Green Building Operations and Maintenance* (JGJ/T 391). By referencing the *Green Building Evaluation Standard* (GB/T 50378), a comparison is made between operational metrics and green building star-level criteria to elevate the level of operational maintenance.

Efforts are directed towards the greening of energy systems. Initiatives include advancing energy-saving transformations in air conditioning systems, strengthening intelligent control and operational optimization, promoting the conversion to intelligent and efficient lighting fixtures, and customizing roof insulation improvements based on local conditions. Additionally, the ecological level of the landscaping system is elevated. Exploiting the carbon-sequestering properties of plants and adhering to water, land, and material conservation principles, conservation-oriented greening techniques are employed. Drought-resistant, pest-resistant native trees, flowers, and grass that suit the soil conditions of the museum campus are planted, utilizing strategies like interstitial plantings, peripheral embellishments, and rooftop greening to increase the courtyard's greenery ratio per unit.

Current estimates indicate that through the greening of energy systems, a carbon reduction of approximately 15 tce can be achieved.

Pathway 3: Strengthening the comprehensive utilization of exhibition resources

Delving deeply into resource recycling, a focus is placed on the cyclic employment of exhibition materials. Conducting thorough inventories of exhibition resources, the museum establishes an integrated material management mechanism encompassing budgeting, procurement, acceptance, allocation, maintenance, and disposal. This integrated approach elevates the level of resource sharing and intensive management, boosting resource turnover rates. Curators and teams maximize the reuse of exhibition materials and materials, refining exhibition evaluation and appraisal standards.

Efforts are directed towards enhancing the efficiency of state-owned assets. Research into assessment methods, standards, and mechanisms for evaluating the security, integrity, and effective use of state-owned assets is conducted to optimize the performance management measures for the allocation, utilization, and disposal of state-owned assets.

There is a focus on reallocating assets to effectively mobilize assets that operate inefficiently or have been idle for an extended period, facilitating the sharing and cyclic utilization of assets to avoid redundant purchases and resource wastage.

Advancing the reduction and recycling of waste in work and life is crucial. Implementing the waste classification system effectively, infrastructure is developed for segregated disposal, collection, and temporary storage alongside establishing a record-keeping system for the amount of waste collected. Continuously promoting paperless office practices, emphasis is placed on enhancing paper management within the office environment.

Pathway 4: Heightening green control and management efforts

Enhancing the construction of an energy metering system is important. For all procurement projects involving energy-consuming equipment, there should be a clear inclusion of the procurement requirements and budget for intelligent metering, alongside their enforcement. This advancement involves revising management measures related to energy procurement projects. Elevating the smart capability of energy management is imperative. By integrating existing building control, energy consumption monitoring, and equipment management systems, and leveraging technologies such as the Internet of Things and the internet, a formidable effort is directed towards crafting an intelligent building control system. This system aims to establish an equipment control platform that combines digitalization, informatization, smart technology, and intelligence.

Strengthening the institutionalized development of product procurement is essential. Strict adherence to prioritizing energy-efficient and environmentally friendly product procurement, along with mandatory procurement regulations, is key. Emphasis is placed on procuring green products such as energy-efficient, low-carbon, and recyclable items, with a preference for resource-integrated products like straw-based environmentally friendly boards. In procurement needs spanning exhibitions, property management, catering, energy-saving contracts, and other services, the focus is on reinforcing green, low-carbon management objectives and service requirements. Gradually establishing a green product supply chain is also a pivotal element of this pathway.

In terms of energy management within Pathway 4, it is estimated that significant energy savings totaling 224,500 kWh can be achieved, leading to a reduction of approximately 135.61 tce in carbon emissions.

Pathway 5: Initiating green and low-carbon demonstration and promotion

The emphasis is on promoting green and low-carbon concepts. By seamlessly integrating the virtues of thrift and conservation with modern green and low-carbon ideologies, innovative promotion techniques are employed to intensify outreach to visitors. This amplification in promotional efforts aims to enhance the effectiveness of communications, fostering the establishment of a museum’s brand for green and low-carbon promotion. Using events like Energy Conservation Promotion Week and Green Travel Promotion Month as platforms, exhibitions centered around carbon peaking and carbon neutrality are planned. Additionally, through reservation service systems, pertinent mini-programs, Weibo, and other new media, the broader society is targeted to propagate the concept of green and low-carbon development, guiding the public towards embracing a green and low-carbon lifestyle.

Cultivating a green and low-carbon lifestyle among cadre and staff members is pivotal. Advocating the green and low-carbon office concept, there is an encouragement for cadre and staff to consciously adopt green and low-carbon office practices, instilling habits of waste separation in daily life. Ensuring efficient dining hall practices, regular campaigns like the "Clear Your Plate" and "No Bottle Waste" initiatives are conducted to combat food wastage. This includes implementing assessment and reporting systems to evaluate the effectiveness of anti-food waste measures in dining halls. Encouraging the increased use of new energy vehicles within the official vehicle fleet, a strong push for public transportation is made, advocating for staff to opt for green commuting methods like public transit, cycling, or walking based on the commuting distance.

In conclusion, with enhancements from Pathways 1 to 5, an estimated overall carbon reduction of approximately 772.45 tce is projected. This achievement not only facilitates the adjustment of the National Museum's energy usage structure but also enhances energy efficiency and promotes awareness towards personnel energy resource conservation. As illustrated in Fig. 4, the adjusted energy structure indicates a decrease of around 5% in traditional conventional electricity consumption, with photovoltaic power comprising approximately 2.48% of the distribution.

Comprehensive analysis and planning for museum decarbonization strategies, ethical considerations, and effectiveness evaluation

Comprehensive analysis and planning for decarbonization strategies

To ensure the smooth implementation and expected outcomes of the National Museum's decarbonization strategies, comprehensive analysis and planning are essential. This involves assessing the technical feasibility, resource requirements, timelines, and

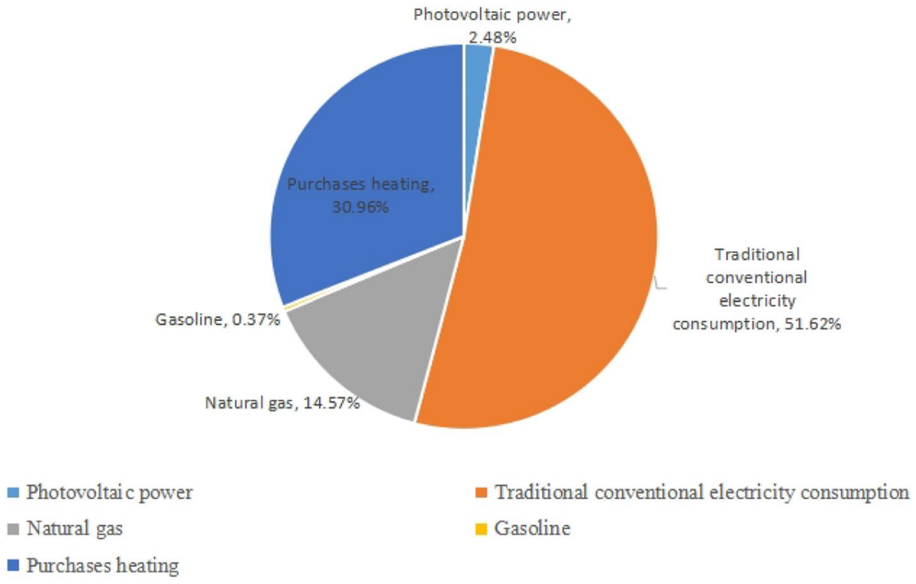

Fig. 4 Energy consumption structure distribution

potential risks of each strategy, such as considering local sunlight conditions and structural load-bearing capacity for the installation of solar photovoltaic systems. Cost–benefit analysis is crucial, necessitating the calculation of initial investment, operational, and maintenance costs for each strategy, and comparing these with anticipated carbon reductions, energy cost savings, and potential government subsidies or tax incentives to ensure a reasonable return on investment. Obstacles that may arise during implementation, such as financial constraints, technical challenges, policy and regulatory limitations, and organizational resistance, must also be identified and addressed. Moreover, the strategies must align with national or local government environmental policies and industry best practices, such as ensuring that energy-saving retrofit measures comply with national green building standards. Effective implementation of these strategies may require multifaceted support, including policy backing, financial investment, technical assistance, and personnel training. Through such in-depth analysis and planning, a solid foundation can be provided for the National Museum's decarbonization strategies, aiding in the achievement of carbon reduction goals and offering valuable insights for other museums.

Addressing ethical considerations in museum carbon reduction

When implementing carbon reduction strategies for museums, it is also necessary to clearly address any ethical issues related to this study. For instance, in the process of promoting electrification and solar energy use, enhancing low-carbon operational standards, strengthening the comprehensive utilization of exhibition resources, reinforcing green control and management practices, and initiating green and low-carbon demonstration and promotion projects, it is important to ensure that these measures do not have negative impacts on the museum's operations, staff, and the public, such as damage to exhibition equipment, deterioration of exhibition quality, or worsening of the working environment for employees. At the same time, it is essential to raise awareness and support for sustainability among staff and the public through training and communication, ensuring that these strategies not only contribute to reducing carbon emissions but are also responsible towards the museum's operations, staff, and the public.

Evaluating museum carbon reduction effectiveness

To more effectively assess the effectiveness of museums in reducing carbon emissions, research can employ various metrics. These include energy consumption per square foot of exhibition space or per visitor to measure energy efficiency; the proportion of renewable energy use and its contribution to the overall energy mix to reflect efforts in sustainable energy utilization; and the scope and impact of sustainable development initiatives such as waste reduction, water conservation, and green building certification, which help reduce carbon emissions and enhance the museum's environmental image and social responsibility. By referencing the practical experience of other museums and comparing the measures and results of energy conservation and emission reduction across different museums, it is possible to find better solutions and promote the industry's development towards a greener and more environmentally friendly direction.

Conclusion

This paper constructs a comprehensive carbon emission accounting model for the operational stage of museums, which includes other indirect emissions, and conducts an accounting analysis using an actual museum as a case study, providing a roadmap for emission reduction. The carbon reduction strategies mentioned in this article align with the "Energy Green and Low-carbon Transition" in the "Action Plan for Carbon Peaking Before 2030", which focuses on vigorously developing new energy sources. The strategies also include "Energy Conservation, Carbon Reduction, and Efficiency Enhancement", aiming to comprehensively improve energy management capabilities, promote energy efficiency and effectivity in key energy-consuming equipment, and strengthen energy conservation in new infrastructure. Additionally, they involve "Circular Economy Facilitating Carbon Reduction" by establishing a sound resource recycling system. These strategies represent the specific policy implementation of these three aspects in the application of museum buildings. It also offers comparisons of emission reduction effects between museums, as well as suggestions for subsequent research content such as improving the data on relevant factors of other indirect carbon emissions within the museum industry. This provides ideas and references for carbon reduction research in the museum sector.

Author contributions

Y.B. contirbuted to Writing- Original draft preparation; X.Y. contirbuted to Data curation; L.Z. contirbuted to Funding acquisition; R.Z. contirbuted to Investigation; N.C. contirbuted to Methodology; X.D. contirbuted to Writing- Reviewing and Editing.

Funding

This work was financially supported by the Director's Fund of the China National Institute of Standardization project "Key Technologies Research and Platform Development Application for Carbon Reduction in Public Institutions" (542023Y-10359), and the Science and Technology Plan project of the State Administration for Market Regulation "Key Technologies Research and Platform Development Application for Carbon Reduction in Public Institutions" (S2023MK0540).

Availability of data and materials

No datasets were generated or analysed during the current study.

Declarations

Ethics approval and consent to participate

Not applicable.

Consent for publication

Not applicable.

Competing interests

The authors declare no competing interests.

Received: 20 May 2024 Accepted: 16 September 2024

References

Alahmad M, Nader W, Yong C et al (2011) Integrating physical and virtual environments to conserve energy in buildings. Energy Build 43(12):3710–3717

An LS (2021) Integrating sustainable development goals: an important direction for the "reshaping" of museums. Southeast Cult 2:10–15

Ang BW, Zhang FQ, Choi KH (1998) Factorizing changes in energy and environmental indicators through decomposition. Energy 23(6):489–495

Bartone EJ, Mendenhall EL Jr, McClutchy JH Jr (2003) System and method for monitoring and controlling energy usage. US Patent and Trademark Office, Washington

Battisti R, Corrado A (2005) Evaluation of technical improvements of photovoltaic systems through life cycle assessment methodology. Energy 30(7):952–967
Cai YQ, Wang Z (2017) Energy-saving design of shanghai natural history museum. Mod Build Electr 8:53–56
Cheng RH (2022) Study on carbon reduction path of green building in full cycle. Jiangsu Sci Technol Inform 39(21):65–69
Chinese Academy of Environmental Planning, Beijing Normal University, Sun Yat-Sen University, China City Greenhouse Gas Working Group (2022) China products carbon footprint factors database. Chinese Academy of Environmental Planning, Beijing
Doukas H, Patlitzianas KD, Iatropoulos K et al (2007) Intelligent building energy management system using rule sets. Build Environ 42(10):3562–3569
Gao CY, Shi JG, Wang FR (2021) Review of carbon emission accounting methods and carbon emission factor in steel production. Contemp Econ Manag 43(08):1–10
IPCC (2006) IPCC Guidelines for national greenhouse gas inventories. Intergovernmental Panel on Climate Change, Geneva
Li FY, Song Q, Shi M et al (2021) Research on the ecological civilization education function and development strategies of natural history museums. Agric Archaeol 2:250–254
National Bureau of Statistics (2000) China input-output table. National Bureau of Statistics of China, Beijing
Shi BW (2015) Museums and social sustainable development: an analysis of the practice of Zhejiang ecological civilization achievement series exhibition. Nat Mus 2:120–123
Shi Y (2019) On the path of sustainable development for museums. Museum 5:93–100
Song XC, An LS (2012) Museums in a changing world: New challenges and insights. Chin Mus 2:2–8
Tang Y, Zhang MT (2022) Research status and development trend of carbon emission standards and specifications. Stand Sci 12:73–76
Wang AP (2022) Research on carbon reduction path of green buildings under dual carbon goals. Resid Real Estate 14:34–37
Wang SY, Song HZ (2022) Museums as actors, promoters, and communicators of sustainable development. Chin Mus 1:125–126
Yang S, Luo SX, Du M et al (2015) Data processing method for public building energy consumption monitoring systems based on data mining. Heat Ventilating Air Cond 45(02):82–86
Yang XH, Li Y, Shi ZY (2023) Research on equipment operation management of the national museum of China based on energy management system. Chin Mus 2:4–11
Zhang YW, Wang XL, Wang XM et al (2019a) Carbon emission accounting method and empirical research based on material balance in agriculture. Chin J Eco-Agric 27(10):1685–1693
Zhang PD, Zhu QG, Shen YL (2019b) Research on carbon emission accounting method based on life cycle. Chin Ind Econ 4:45–62
Zhao Y (2019) Challenges and opportunities for geological museums in ecological civilization construction. N Chin Nat Res 2:132–133
Zhao XL, Zhu JH, Wang H (2013) Research on carbon emission accounting method for road transport industry based on actual measurement method. Environ Sci Technol 36(12):207–211

Publisher's Note