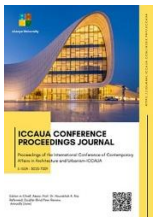

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Towards a Sustainable Museum: Integrating Scenography and Technology in the Museum Experience

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A b s t r a c t

The rapid advancement in digital technologies, along with the growing global interest in sustainability issues, has fundamentally transformed contemporary museum design. Museums have evolved beyond static display venues into dynamic, interactive environments that demands rethinking both spatial organization and visitor experience quality. Despite this evolution, a significant gap persists in the literature: few studies have systematically examined how sustainability principles and scenographic design strategies can be integrated within museum environments to achieve both environmental performance and experiential excellence. This study addresses that gap by proposing a comprehensive design framework the Sustainable Scenography Index (SSI) that synthesizes sustainable design principles and scenographic strategies to improve environmental performance and elevate visitor experience. The study employs a qualitative comparative methodology applied to six internationally recognized museums: the Natural History Museum London, Naturalis Biodiversity Center, California Academy of Sciences, Vitra Design Museum, National Museum of Qatar, and the Grand Egyptian Museum. Data were drawn from institutional sustainability reports, peer reviewed literature, and professional documentation, analysed across four thematic dimensions: energy and material efficiency, circular scenographic design, visitor eco-literacy, and institutional governance. The findings demonstrate that integrating digital and immersive technologies with sustainable design practices contributes to improved thermal comfort, enhanced educational efficiency, and reduced environmental impact. The study makes an original contribution by introducing the SSI as replicable, context evaluation framework applicable to diverse institutional contexts, including global mega museums. The study results show that integrating digital and experimental technologies with sustainable design practices contributes to improving thermal comfort, increasing the efficiency of the educational process, and reducing negative environmental impacts.

K e y w o r d s : Scenography; Digital Scenography ; Interior Design; Sustainable Museums; Museography..

1. Introduction

Museums in the twenty-first century have evolved from traditional spaces for preserving artifacts into interactive environments that combine education, culture, and visitor engagement. This transformation has been influenced by technological advancements, shifting visitor expectations, and the increasing global focus on sustainability. In this context, scenography plays an important role in shaping museum experiences using spatial design, lighting, visual communication, and narrative elements that enhance emotional and educational interaction within exhibition spaces. (Janes & Sandell, 2019) Scenography, as a multidisciplinary practice that combines spatial design, lighting, visual communication, sound, and narrative techniques, plays a significant role in enhancing the emotional and cognitive interaction between visitors and museum spaces. Through the strategic organization of space and atmosphere, scenography contributes to creating memorable and meaningful experiences while supporting educational and cultural objectives. (McKinney et al., 2017) Simultaneously, contemporary technologies such as digital projection, interactive media, augmented reality (AR), virtual reality (VR), and smart environmental systems have expanded the possibilities of exhibition design by enabling adaptable, immersive, and resource-efficient museum environments. (Balzani et al., 2023). The intersection of scenography and sustainability represents an underexplored dimension of museum studies. Existing literature has addressed sustainability in museums primarily through the lens of energy management and material efficiency (Kramer et al., 2022; Chiantore & Poli, 2021), while scenographic research has focused predominantly on experiential and aesthetic dimensions (McKinney et al., 2017). Few studies have systematically examined the extent to which scenographic strategies can themselves function as instruments of environmental performance improvement and sustainability communication (Nassef et al., 2023). This study addresses that gap through a comparative analysis of six internationally recognized museums, proposing the Sustainable Scenography Index (SSI) as a novel multi-criteria evaluation framework. The SSI operationalizes the relationship between sustainable design and scenographic practice across five weighted dimensions, enabling systematic comparison across diverse institutional contexts including,

critically, a global mega museum. The study makes the three original contributions, first it proposes the SSI as a replicable diagnostic tool for assessing sustainable scenographic practice across diverse institutional contexts. Second, it introduces the GEM as a casestudy for evaluating sustainability in global museum contexts, addressing a significant gap in comparative museum literature. Third, it empirically demonstrates that sustainability and visitor experience quality are mutually reinforcing rather than competing objectives in museum design. This paper explores the role of integrating scenography and technology in developing sustainable museum experiences. It examines how innovative exhibition strategies can contribute to environmental, social, and cultural sustainability while enhancing visitor interaction and spatial experience. Furthermore, the study investigates contemporary museum practices and analyzes the ways in which digital technologies and scenographic principles can collectively redefine the future of museum design in a more sustainable and experiential manner. (Falk & Dierking, 2016)

2. Literature Review

2.1. Sustainability in Modern Museums

Sustainable museum practice has emerged as a critical framework for reconciling cultural heritage preservation with contemporary environmental imperatives. The concept of museum sustainability encompasses four interconnected dimensions: environmental sustainability, which concerns energy consumption, material use, and carbon emissions; social sustainability, which relates to accessibility, community engagement, and cultural equity; economic sustainability, which addresses long-term operational viability and cultural sustainability, which encompasses the preservation, presentation, and renewal of tangible and intangible (Janes & Sandell, 2019) The introduction of cultural sustainability as a fourth pillar reflects a growing consensus in the museum studies literature that heritage preservation and cultural vitality are not merely the purposes of museum activity but are themselves sustainability objectives requiring dedicated governance and measurement framework. In the domain of energy efficiency, the adoption of Light Emitting Diode (LED) lighting systems represents a significant technological advancement, as LEDs consume up to 75% less energy than conventional incandescent sources while providing precise spectral control essential for artifact preservation. The strategic integration of natural daylighting and smart climate control systems employing sensor-driven automation further reduces energy consumption while maintaining conservation grade temperature and humidity parameters (Kramer et al., 2022). With respect to material sustainability, the selection of recyclable, reusable, and low impact materials including sustainably sourced timber and modular exhibition structures directly reduces the embodied carbon associated with exhibition construction and decommissioning (Chiantore & Poli, 2021). Modular design systems enable the iterative redeployment of exhibition components across multiple installations, substantially reducing construction waste.

In terms of waste reduction, the substitution of static printed materials with dynamic digital display technologies diminishes paper consumption while enhancing visitor engagement through interactive content delivery. Collectively, these strategies contribute to reducing institutional carbon emissions, improving indoor air quality, and advancing the integration of renewable energy technologies within museum infrastructure, positioning cultural institutions as active contributors to global sustainability transitions (Nassef et al., 2023). Museums also function as significant economic actors within their host communities, attracting cultural tourism, stimulating local employment, and partnering with creative industries roles that extend their sustainability contribution well beyond the boundaries of their own operations (Gustafsson & Ijla, 2017). Recent scholarship has also drawn attention to the social and cultural dimensions of museum sustainability. Falk and Dierking (2016) argue that the visitor experience itself is a sustainability issue: museums that fail to engage visitors meaningfully can't fulfil their cultural mission over the long term. This perspective connects institutional sustainability to the quality of the spatial and experiential environment a domain where scenography plays a decisive role. Complementing this view, Pop and Borza (2015) demonstrate that a museum's long-term sustainability depends not only on resource efficiency but on its capacity for entrepreneurial adaption aligning programs, services and spatial design with the evolving needs of its community. Their research on Romanian museums further reveals that the absence of systematic sustainability measurement frameworks including indicators spanning collection conservation, visitor engagement, and earned income leaves institutions unable to diagnose performance gaps or benchmark progress, a limitation that the SSI framework proposed in this study directly addresses.

2.2. The Role of Scenography in Museum Design

Scenography is the creative design exhibition spaces, encompassing lighting, colour, materials, sound, digital media, spatial arrangement, and narrative technique to shape how visitors experience exhibitions emotionally and intellectually (McKinney et al., 2017). Historically rooted in theatrical set design, scenography has been progressively adopted in museum and exhibition contexts as practitioners recognized its capacity to transform information into immersive experience (Giannachi et al., 2012). The primary functions of scenography in museum contexts can be understood across four dimensions. First, scenography supports storytelling by enabling the presentation of historical, artistic, or scientific content through spatially organized visual narratives that connect emotionally with visitors (Bedford, 2001). Second, it creates immersive experiences by deploying lighting, sound, projection mapping, interactive screens, and spatial to produce environments that promote active visitor engagement. Third, scenographic elements particularly digital and interactive installations increase curiosity, participation, and educational retention (Lehn & Heath, 2005). Fourth, contemporary scenographic practice increasingly supports environmental sustainability through the use of reusable modular systems, energy efficient lighting, digital substitution for physical materials, and flexible spatial configuration. (Gadsby, 2014)

The integration of digital technologies has substantially expanded scenographic possibilities. Augmented reality overlays, immersive projections environments, holographic displays, and responsive lighting systems now enable exhibition designers to create compelling experiential environments while reducing material consumption and energy use. The Museum of Art and Light known as (MoA+L), which opened in Manhattan, Kansas in November 2024, exemplifies this

convergence: 34-foot-high digital display as shown in Fig(1,2), it create immersive environments that replace conventional physical set construction, significantly reducing material waste while intensifying the visitor experience (Mason, 2022).

Figure 1. The digital interior space in Museum of Art and Light.
Source : https://www.artlightmuseum.org/moal-diversified-partner-in-kansas-immersive-digital-museum-experience/

Figure 2. The digital interior space in Museum of Art and Light.
Source : https://www.artlightmuseum.org/moal-diversified-partner-in-kansas-immersive-digital-museum-

2.3. Relationship Between Sustainability and Digital Scenography

The relationship between sustainability and digital scenography operates through several interconnected mechanisms. Digital scenography reduces material waste by replacing physical exhibition elements as printed graphics, constructed sets, disposable display materials, with reusable, updatable digital content deployed by projection mapping, LED screens, and virtual environments (Bedford, 2001). This substitution reduces the consumption of raw materials, transportation costs, and construction waste associated with temporary exhibition. Digital scenographic systems also contribute to energy efficiency by employing LED lighting, smart environmental controls, and automated management technologies that consume less energy than conventional alternatives while enabling more precise regulation of temperature, humidity, and lighting conditions (Beer et al., 2024). The long-term flexibility of digital system which can be updated without physical reconstruction further reduces the environmental impact of exhibition renewal overtime.

From a social sustainability perspective, digital scenography enhances accessibility and inclusivity by enabling multilingual, multisensory, and adaptive exhibition interfaces that serve diverse visitor populations Museums that proactively, extend their reach to underrepresented and culturally isolated communities including refugees, people with disabilities, and socially marginalized groups thereby strengthen social capital and foster the sense of collective identity that underpins long term institutional relevance (Gustafsson & Ijla, 2017). The remote accessibility afforded by virtual museum environments additionally reduces transportation associated carbon emissions while access to cultural heritage (Balzani et al., 2023). At the building level, the design of green museums, Fig. (3), as exemplified by the Amazwe Museum of South African Literature, the first public building in South Africa to receive a five-star rating from the South African

Green Building Council, demonstrates how sustainable architecture itself conveys institutional values to the communities that museums serve. (Thomas, 2024)

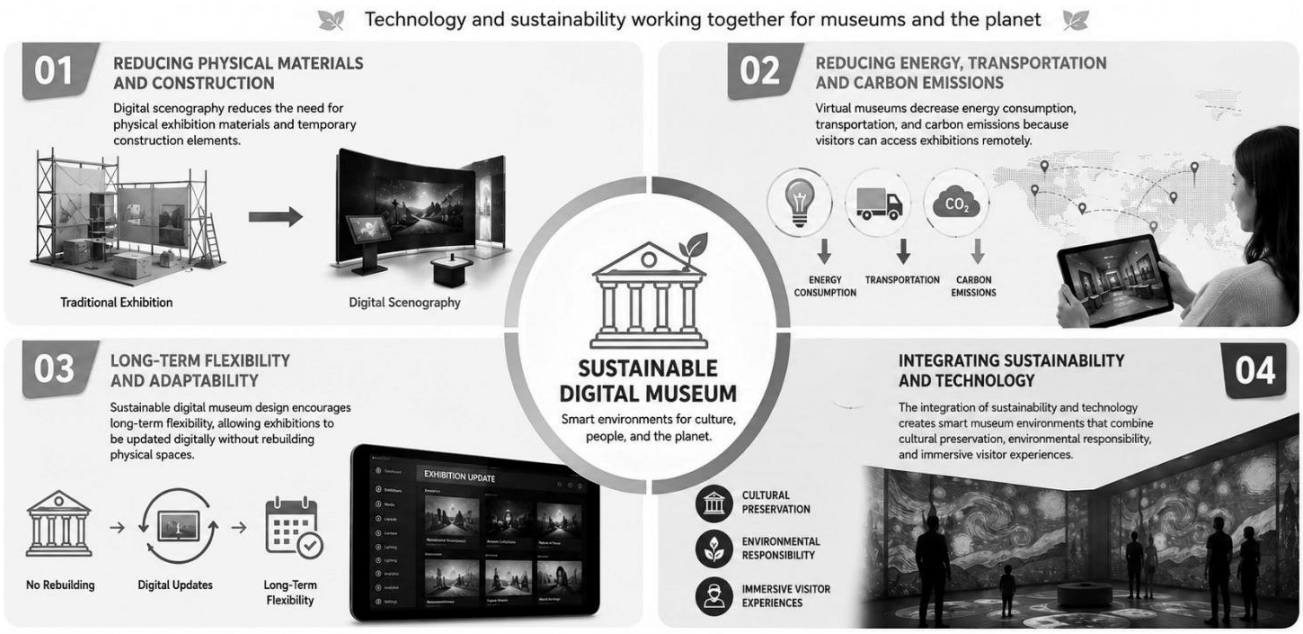

Figure 3. The relationship between sustainability and scenography.
Source : Author

2.4. Storytelling, Sustainability and Visitor Engagement

Storytelling is a communication approach that conveys ideas, values, and experiences through narratives that emotionally and intellectually engage audiences. In design, museums, architecture, and digital scenography, storytelling transforms information into meaningful experiences by connecting users or visitors with cultural, social, or environmental themes. (Bedford, 2001) It is not only a method of presenting content, but also a strategy for creating emotional interaction, memory, and awareness. Sustainability refers to the practice of meeting present needs without compromising the ability of future generations to meet their own needs. It is based on three interconnected dimensions: environmental sustainability, social sustainability, and economic sustainability. Within museums and exhibition design, sustainability focuses on reducing environmental impact, promoting cultural preservation, encouraging responsible resource use, and creating long-lasting adaptable spaces. (Janes & Sandell, 2019).

The relationship between storytelling and sustainability lies in storytelling's ability to communicate sustainable values and influence human behavior. Sustainable concepts often involve complex environmental and social issues that may be difficult for audiences to fully understand through data and technical information alone. Storytelling helps simplify these concepts by presenting them through immersive narratives, emotional experiences, and interactive engagement. As a result, audiences become more connected to sustainability issues and more aware of their role in supporting sustainable practices. Al-Malik and Yaqout (2018) demonstrate that interactive infographic design within museum contexts enhances the communication of complex thematic content, including environmental narratives.

In museums and digital scenography, storytelling supports sustainability by creating meaningful visitor experiences using interactive media, projection mapping, virtual reality, sound, lighting, and spatial narratives. These techniques can reduce dependence on physical materials and temporary construction while enhancing visitor engagement. Sustainable storytelling also encourages the reuse of exhibition components, flexible spatial systems, and digital interpretation methods that minimize waste and energy consumption. (Ahmed, 2024) The Museum of the Future in Dubai is example number 4&5. One of the most prominent global models in applying virtual digital scenography, where it combines smart architecture and immersive technologies to create a unique museum experience. The role of scenography here is not limited to displaying content; it extends to becoming part of an interactive narrative that simulates the museum's vision as a living laboratory for the future. (Al-Adawi, 2024)

Figure 4. The hall lighting automatically adjusts to different colours based on the displayed theme (such as blue for technology, green for sustainability).
Source : https://museumofthefuture.ae/ar

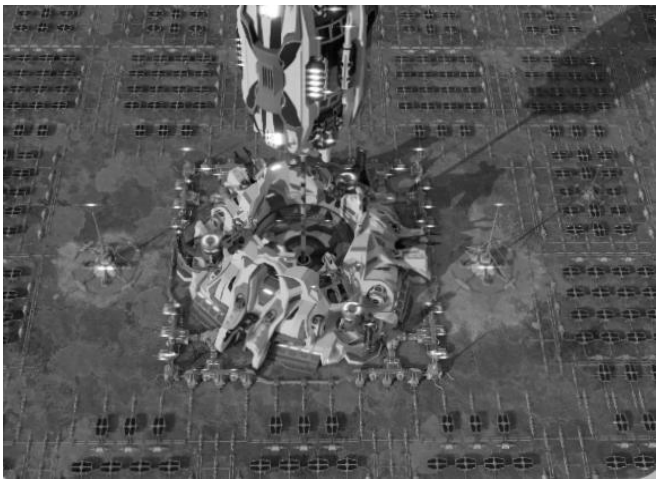

Figure 5. It demonstrates the experience of "travelling to the year 2071" using virtual reality (VR) glasses.
Source : https://museumofthefuture.ae/ar

Comparative Analysis of Six international museums were selected due to their recognized contributions to sustainable exhibition environments and innovative scenographic systems .

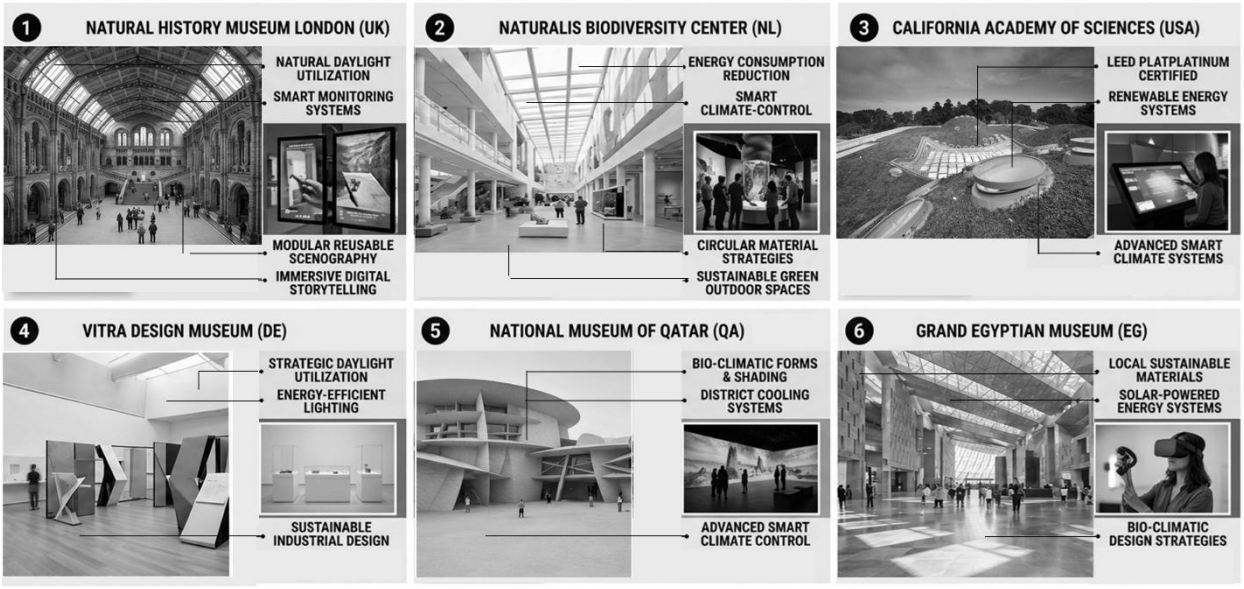

Figure 6. Shows the six international case study museums used in research.
Source : Author

3. Methodology

3.1. Research design

This study adopts comparative analysis for several case studies; the case study methodology is well-suited to investigate complex and context that characterize sustainable scenographic practice within museum institutions. Comparative case analysis allows the identification of patterns across different cases and analytical generalizations that transcend the particularities of individual cases, while remaining sensitive to contextual factors that quantitative approaches would obscure

The methodological framework proceeds through four sequential phases: (1) theoretical framework development, in which the conceptual foundations of the SSI were established through systematic literature review; (2) case selection and data collection; (3) analytical framework application, in which each case was scored against the SSI's 20 sub-indicators; and (4) comparative synthesis, in which cross-case patterns were identified and interpreted in relation to the theoretical framework. This sequential structure ensures transparency and replicability of the analytical process.

3.2. Data Collection

The data were collected from different sources such as institutional documents including annual sustainability reports and published Environmental Management Plans, provided professional documents provided by organizations including the Museums Association. Also, academic literature as peer reviewed studies on sustainable museum practices, exhibition design and environmental assessment, provided theoretical and empirical context. Professional documentation from organizations, including the Museums Association and ICOM provided sector level benchmarking data. It's acknowledged that this study relies substantially on self-reported institutional data, which may reflect presentational biases. This limitation is addressed through triangulation across multiple source types and through the explicit identification of cases where evidence quality was insufficient to support confident scoring.

3.3. Case Selection

Six cases were selected on the basis of three criteria: (i) international recognition as significant practitioners in sustainable museum operations or as emerging cases of global importance, (ii) availability of documents and (iii) diversity in the geographic region, collection type, building typology, institutional scale and development context.

The selected cases are:

- National History Museum London (NHM), United Kingdom
- Naturalis Biodiversity Center, Leiden, Netherlands
- California Academy of Sciences, San Francisco, USA
- Vitra Design Museum, Weil am Rhein, Germany
- National Museum of Qatar, Doha, Qatar
- Grand Egyptian Museum (GEM), Giza, Egypt

3.4. The Sustainable Scenography Index (SSI) - Analytical Framework:

Each case was analysed across four thematic dimensions such as (1) Energy and Material Efficiency, (2) Circular Scenographic Design, (3) Visitor Eco-Literacy and Engagement, (4) Institutional Governance of Sustainability. These dimensions were operationalized into 20 sub indicators, each scored on a five-point scale, yielding ab aggregate Sustainable Scenography Index (SSI) score for each institution. The SSI framework consists of main points such as the energy source, scenography model, CO2 reduction target, digital Integration, waste policy and visitor engagement.

The SSI was developed as a multi-criteria evaluation framework for systematically assessing sustainable scenographic practice across museum institutions. The framework draws on a lineage of indicator-based sustainability assessment tools in the museum literature, including the 33-indicator model proposed by Pop and Borza (2016) and the scoring matrix approach applied by Ashour and Seif Al Nasr (2021) to evaluate sustainability performance in museum buildings across five criteria dimensions. The framework comprises five thematic dimensions, each assigned a weight reflecting its relative importance in determining overall sustainability performance, as presented in Table 1.

Table 1. Shows the five key dimensions of Sustainable Scenography Index (SSI); source: author analysis.

Dim.	Title	Weight	Key Indicators
D1	Energy & Carbon Performance	25%	Renewable energy share; CO2 intensity per visitor; carbon offset quality
D2	Scenographic Circularity	25%	Material reuse rate; modular system adoption; supplier chain traceability
D3	Visitor Eco-Literacy & Engagement	20%	Environmental narrative depth; post-visit behaviour surveys; participatory elements
D4	Institutional Governance of Sustainability	20%	Existence of sustainability policy; reporting transparency; staff training
D5	Innovation & Replicability	10%	Pilot projects; published methodology; cross-institutional knowledge transfer

Each sub-indicator within the five dimensions is scored on a five-point scale (0 = absent/no evidence; 1 = nascent/minimal; 2 = developing; 3 = established; 4 = advanced; 5 = exemplary/leading practice). The weighted scores are aggregated to produce a composite index out of 100. The SSI is intended as a diagnostic and comparative tool, not a

ranking or certification system. Its primary value lies in identifying specific dimensions of sustainable scenographic practice where individual institutions are performing strongly or where improvement is needed. The SSI is designed to be adaptable across institutional contexts, including mega-museums in the Global South. The authors recommend that contextual modifiers be applied transparently when assessing institutions facing structural constraints extreme climate, fossil-fuel grids, showed figure (7), nascent governance frameworks that lie outside the control of the institution's leadership.

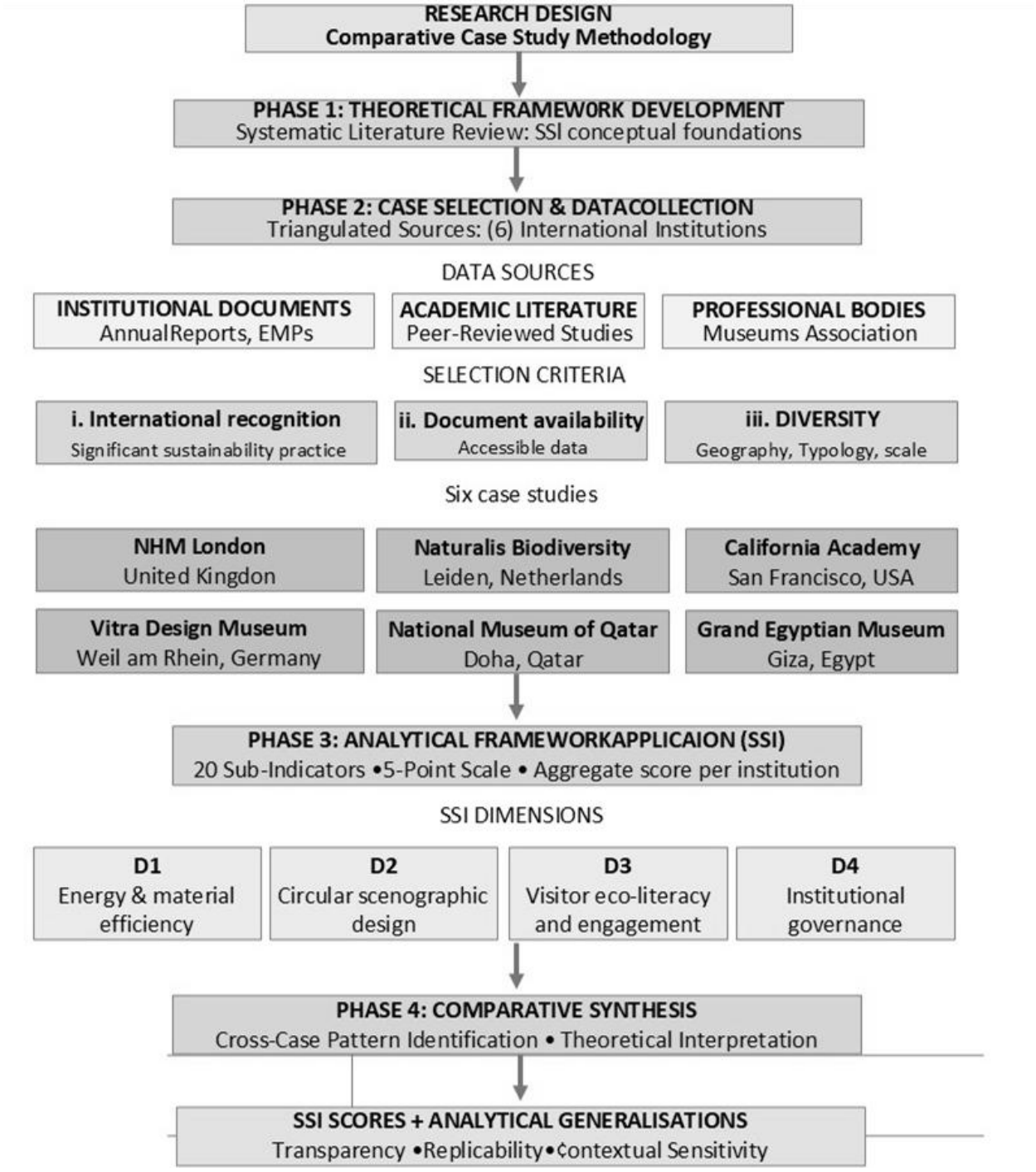

Figure 7. Shows the graphical methodology diagram.
Source : Author

4. Results

4.1. Case Study Projects

Before presenting the consolidated comparative results, this section profiles each of the six case institutions individually, situating their sustainability strategies within their specific institutional, climatic, and development contexts. This narrative grounding is intended to make the subsequent SSI scores in section 4.2 easier to interpret beyond their numerical values and to illustrate the qualitative dimensions that are inevitably compressed within a composite index.

A. Natural History Museum London (NHM), United Kingdom

The Natural History Museum in London is one of the world's leading institutions in the field of preserving and documenting biodiversity. Its vast collections, accumulated over centuries, constitute invaluable scientific resources for taxonomy, methodology, and research into the history of life on Earth. (Naggs, 2022) Based on the Natural History

Museum's Long History Book and Accounts Report 2022–2023, the museum has integrated sustainability into its outstanding masterplanning with the "Sustainable by Nature Plan," which aims to achieve net-zero carbon emissions by 2035. This aligns with the UK government's environmental sustainability goals, emphasizing the integration of sustainability into all new and ongoing projects from the very first year of design. Key initiatives in this area include the Urban Nature Project in South Kensington and the associated Science Centre and Digitalization Project. These major projects incorporate sustainability-specific performance considerations, including climate change impact, resource use, welfare, corruption, and procurement. These promising efforts reflect the museum's commitment to minimizing its footprint while ensuring its facilities support the achievement of its long-term sustainability goals. (Natural History Museum, 2023) The NHM achieved the second-highest SSI score among the six cases (78/100), reflecting consistent strength across energy performance, circularity, and engagement rather than excellence concentrated in a single dimension.

B. Naturalis Biodiversity Center, Leiden, Netherlands

The museum is undergoing a comprehensive renovation and expansion, integrating its scientific research facilities, natural collections, laboratories, and public exhibition halls into a single complex. The design has long prioritized sustainability, utilizing natural materials such as wood, glass, steel, and concrete, while also incorporating flexible spaces to minimize the building's footprint and visitor capacity. The museum's core mission is to "study existence in order to achieve biodiversity," making sustainability an integral part of the building's identity and function. (Pintos, 2020)

Sustainability is also reflected in the National Museum's vision and operations. The Naturalis Biodiversity Centre, established in its strategic plan (2021–2024), commits to contributing to the resolution of global environmental challenges such as climate change and biodiversity loss through scientific research and community outreach. The Centre describes itself as an institution dedicated to guiding society toward a more sustainable future by developing and widely disseminating scientific knowledge. In addition, the center indicates that its new building is more energy-efficient compared to the previous building, while successfully following innovative practices in work, management and employee behavior, including producing its role as a model for the cultural and scientific company. (Naturalis Biodiversity Center, 2021) This focus on participatory science aligns with Gustafson and Igla's (2016) characterization of museums as institutions that promote environmental awareness through active community engagement rather than passive transmission. Naturalis scored 74/100 on the SSI, with relative strength in recycling and visitor engagement balanced by moderate digital integration and energy performance.

C. California Academy of Sciences, San Francisco, United States

The architectural reconstruction of the California Academy of Sciences in San Francisco embodies a holistic approach to sustainable material lifecycles and environmentally conscious urban design. On-site material interventions began with the selective demolition of older facilities with a fifty-year development history, enabling extensive material recovery and recycling. The new building's structure incorporates a high proportion of reclaimed landfill waste and sustainable materials, including a main steel frame composed of 90% recycled metals. Furthermore, thermal insulation was achieved using recycled waste in the form of thick cotton padding made entirely from recycled blue jeans. (Flannery & Smith, 2011; SUPSI, 2014) The visible exterior cladding complements this resource-conscious philosophy, employing a utilitarian use of light gray architectural concrete. This structural approach explicitly prioritizes functionality over decorative cladding, providing a low-impact backdrop for public educational exhibits. (Flannery & Smith, 2011)

In parallel with the selection of low-impact materials, the institution employs passive environmental control systems and building-integrated photovoltaics (BIPV) to significantly reduce long-term operational energy consumption. A central element of this strategy is the undulating, multi-layered "living roof," covered with approximately 1,700,000 drought-tolerant native plants that require no conventional irrigation once established. (SUPSI, 2014) This plant infrastructure acts as an insulating barrier and passive cooling agent, working in conjunction with a series of automated skylights that respond to environmental indicators to replace conventional air conditioning with a natural ventilation system. (Flannery & Smith, 2011; SUPSI, 2014) This configuration allows natural light to penetrate successfully through 90% of all occupied spaces in the museum. To generate clean energy on-site, the edges of the green roof extend into a semi-transparent solar canopy incorporating more than 55,000 microcrystalline photovoltaic cells. This integrated photovoltaic system serves a dual purpose; It provides a unique shading effect to regulate natural light, while generating an estimated 213,000 kilowatt-hours of electricity annually. This sustainable production covers nearly 15% of the facility's total energy needs, culminating in the project achieving the largest LEED Platinum certification in the world. (SUPSI, 2014)

D. Vitra Design Museum, Germany

Merging sustainability with architectural longevity, the Vitra Design Museum in Germany features Frank Gehry's design with natural daylight and a diverse campus landscape. Corporate initiatives, including circular design principles in sustainability reporting, focus on reducing environmental impact and promoting environmental awareness. Vitra combines photovoltaic and geothermal energy systems with a carbon-neutral operations target for 2030. As a design-focused organization, its sustainability strategy is most notably characterized by a long-life design philosophy and a formal furniture lifecycle plan that extends the operational life of both exhibition and institutional furniture. (Vitra, 2020) This places Vitra (70/100) as a case where landscape control, rather than technological extremism, is the prevailing sustainability strategy, reinforcing SSI's hypothesis that circular economy and energy performance can be achieved through markedly different design philosophies depending on the corporate mission.

E. National Museum of Qatar (NMoQ), Doha, Qatar

The National Museum of Qatar integrates environmentally friendly practices and appropriate material selection into its modern museum framework. In its natural environment exhibits, the museum displays over 600 lifelike miniature

models of local plant and animal species, carefully crafted from durable, non-toxic materials, including resin, fiberglass, and plaster. By choosing these harmless components, the museum ensures long-term structural stability while minimizing environmental degradation. This design philosophy aligns perfectly with the museum's commitment to environmentally conscious display practices, demonstrating how contemporary cultural centers can leverage sustainable materials science to preserve natural history without contributing to environmental damage. (Al-Majid et al., 2025) NMoQ has received recognition for its environmental performance, such as the LEED Gold certification and Global Sustainability Assessment System (GSAS).The NMoQ SSI score of 55/100 should be read in light of the structural constraints on energy under an extreme climate and a fossil fuel-adjacent network context, constraints that are largely outside the scope of direct institutional control, consistent with the contextual rate principle proposed in Section 3.4.

F. Grand Egyptian Museum (GEM), Giza, Egypt

The Grand Egyptian Museum (GEM) stands as a leading and prominent example of environmentally friendly cultural infrastructure, having been specifically designed and constructed to function as a sustainable and economically robust building (Nassef et al, 2023). As the first officially recognized eco-friendly museum in Egypt, the GEM has successfully integrated rigorous international standards into its operations and obtained prestigious ISO certifications in environmental management (ISO 14001:2015), quality management (ISO 9001), and occupational health and safety (ISO 45001:2018) (Nassef et al., 2023). Beyond these construction and environmental achievements, the museum adopts a multidimensional approach to achieving social and economic sustainability, aligning with the United Nations Sustainable Development Goals and Egypt's Vision 2030 (Nassef et al., 2023; Taher et al, 2024). Instead of functioning as a traditional, rigid repository for artifacts, its architectural model incorporates comprehensive recreational, commercial, and educational areas that strongly promote long-term community engagement and regional economic growth (Nassef et al., 2023). Through proactive digital public relations campaigns, community educational workshops, and interactive display strategies, the Grand Egyptian Museum successfully breaks down traditional barriers between cultural institutions and the public, establishing a flexible framework that directly supports the preservation of ancient heritage, local identity, stakeholder engagement, and the modern ecosystem of ecotourism (Taher et al., 2024).

4.2. Comparative Analysis Overview

Table 2 presents a consolidated comparison of the six case studies across the key analytical dimension together with Sustainable Scenography Index (SSI) scores derived from the full 20-indicator assessment. The scores reflect the authors' analysis of available institutional documentation and published literature.

Table 2. Comparative overview of sustainability and scenographic practices across six case studies (SSI scores on a 100 point scale); source: author analysis.

Criterion	NMoQ Qatar	NHM London	Cal Academy Usa	Naturalis NL	Vitra DE	GEM Egypt
Energy Source	District cooling+solar	100% renewable (2022)	LEED Platinum solar	Partial solar + grid	PV + geothermal	Grid + solar (partial)
Scenography Model	Hybrid trad/digital	Modular reuse system	Living building integerated	Circular material flows	Long-life design	Monumental+ immersive AV
CO2 Reduction Target	15% by 2028 (State plan)	50% by 2030 (vs 2019)	Net zero operations	30% by 2027	Carbon- neutral by 2030	Aligned with Egypt Vision 2030
Digital Integeration	High (immersive)	High (AR, interactive)	High (living labs)	Medium	Medium (archival)	High (holographic/VR)
Waste Policy	Developing framework	Zero-waste target	On-site composing + reuse	Material passport system	Furniture lifecycle plan	Early-stage policy
Visitor Engagement	Cultural sustainability	Eco-galleries + pledges	Nature immersion zones	Science participation	Design literacy focus	Heritage + env. narrative
SSI Score (author)	55/100	78/100	82/100	74/100	70/100	52/100

4.3. Cross-Case Patterns

The comparative analysis reveals several cross-cutting patterns. First, the most consistently high-performing institutions as Cal Academy and NHM London are characterized not only by excellence in any single dimension but by integration across all four analytical areas. This finding is consistent with Janes and Sandell (2019) argument that sustainability in museums requires systemic institutional transformation rather than technical optimization, and aligns with Pop and Borza's(2016) finding that equilibrium across cultural, social, economic, and environmental pillar rather than maximization of any single dimension represents the authentic measure of museum sustainability.

Second, the digital/physical balance in scenographic strategy emerges as nuanced rather than straightforwardly deterministic. While high digital integration is associated with reduced physical material consumption, the ecological

value of direct natural encounter CalAcademy's living exhibits, Naturalis's citizen science model suggests that digital displacement of nature is not always a sustainability gain. The most successful strategies use digital technologies selectively and purposefully.

Third, the inclusion of the GEM introduces a dimension of analysis largely absent from the existing comparative literature: the sustainability challenges and opportunities of mega-museum institutions in Global South contexts. The GEM's SSI score of 52/100 should be contextualized against the extraordinary scale of its collections mission, the constraints of its national energy infrastructure, and the early stage of its operational sustainability governance. The GEM scores relatively well on indicators most directly within its institutional control local material sourcing, digital scenographic displacement of physical infrastructure, and nascent heritage-environment interpretive connections suggesting a foundation on which a more comprehensive sustainability strategy can be built.

Fourth, the comparison between the NMoQ (55/100) and the GEM (52/100) is instructive: both institutions face extreme climate challenges, both are in early stages of sustainability governance development, and both deploy high-intensity digital scenography as a primary exhibition strategy. The proximity of their scores suggests that institutions in comparable development contexts face structurally similar sustainability challenges warranting dedicated research and knowledge-exchange frameworks.

5. Discussion

5.1. Towards an Integrated Model of Sustainable Museum Design

The findings of this comparative analysis point towards an integrated model of sustainable museum design in which the scenographic environment is understood not merely as a context for displaying objects but as an active instrument of environmental communication and institutional values. This perspective aligns with the concept of the activist museum proposed by Janes and Sandell (2019), in which cultural institutions deploy their authority, platforms, and spaces in the service of social and environmental justice. It also connects to the growing literature on experience economy approaches to museum design, which emphasize the transformative potential of immersive, participatory, and emotionally resonant visitor experiences that sustainable scenographic environments, when well designed, can deliver. (Falk & Dierking, 2016)

The results extended existing literature in three important ways. First, prior studies have tended to address sustainability and visitor experience as parallel but separate concerns; this analysis demonstrates their deep interdependence when scenography serves as the mediating design practice. The four-pillar sustainability framework articulated by Pop and Morza(2016) cultural, social, economic, and environmental provides a productive theoretical complement to SSI, reinforcing that scenographic design decision carry consequences across all four dimensions simultaneously. Second, the SSI framework operationalizes this integration in a form that is measurable, comparable, and actionable advancing beyond the qualitative frameworks that characterized most existing museum sustainability scholarship (Chiantore & Poli, 2021). The 33 indicator relative measurements model developed by Pop and Borza (2016), which benchmarks individual museum performance against sector leaders rather than applying absolute thresholds, informed the SSI's similarly relative and comparative scoring logic. Third, the inclusion of GEM and NMoQ as case studies addresses the systematic underrepresentation of Global South institutions in comparative museum research, a gap identified but not resolved by previous studies.

5.2. The GEM and sustainability in Global South Contexts

The GEM case adds a further dimension to this model: the possibility that the ecological narratives embedded within ancient heritage collections such as the agricultural systems, material cultures, and landscape relationships of pre-modern civilizations, offer interpretive resources for sustainability communication that are both culturally resonant and intellectually distinctive. A museum that can simultaneously communicate the achievements of ancient Egyptian environmental management and the contemporary urgency of water scarcity in the Nile Valley occupies a uniquely powerful position in the public communication of sustainability. (Abdel Hamid, 2022)

The inclusion of the GEM in this comparative analysis raises methodological questions that deserve explicit attention. The application of sustainability evaluation frameworks developed primarily with reference to European and North American institutions to a mega-museum in Egypt risks reproducing the epistemic hierarchies that post-colonial scholarship has critiqued in heritage studies more broadly. An SSI score of 52/100 for the GEM, if presented without contextual qualification, could be misleading: it reflects the constraints of national energy infrastructure and governance development trajectories that are not within the GEM's institutional control, not a failure of will or ambition.

Future iterations of the SSI framework should develop context-adjusted benchmarks that enable more equitable comparison across different national development contexts. This might involve separate benchmark bands for institutions in high-income, upper-middle-income, and lower-middle-income country contexts, or a contextual modifier coefficient applied to SSI scores before cross-national comparison. The museum sustainability research community has an obligation to develop evaluation tools that are genuinely global in their applicability, rather than tools that inadvertently penalize institutions for the structural conditions of the countries in which they operate.

5.3. Practical Implications for Museum Professionals

For museum professionals, comparative analysis yields several actionable implications. First, the adoption of a modular, component-based approach to exhibition infrastructure is the single most impactful scenographic intervention available to institutions of any scale. Second, the integration of sustainability themes into interpretive strategies, rather than their isolation in designated eco galleries, generates stronger visitor engagement and retention outcomes. Third, the appointment of a dedicated sustainability officer with cross-departmental authority is a consistently significant predictor of institutional sustainability progress. Fourth, for newly established mega-museums like the GEM, the early formalization of a sustainability governance framework including an Environmental Management Plan, a published

carbon inventory, and a sustainable procurement policy, is a priority investment that yields compounding returns as the institution matures. (Khalil Ebrahim, 2024)

6. Conclusion

6.1.

This paper has examined the intersection of sustainability and scenography in contemporary museum practice through a comparative case study analysis of six internationally recognized institutions. The analysis demonstrates that leading museums are developing increasingly sophisticated strategies for reducing the environmental footprint of their exhibition production and operations, while simultaneously deploying sustainable scenographic environments as powerful instruments of environmental communication and public engagement.

The proposed Sustainable Scenography Index (SSI) offers a replicable multi-criteria framework for assessing and comparing sustainable scenographic practice across diverse museum contexts. The SSI scores generated in this study are indicative rather than definitive reflecting the limitations of self-reported institutional data and the need for contextual modifiers in cross-national comparison. It provides a useful baseline for the more systematic evaluation that the global museum sector urgently requires.

The Grand Egyptian Museum represents both a significant challenge and a remarkable opportunity for sustainable museum practice. Its challenges a fossil-fuel-dependent national grid, an extreme desert climate, and the complexity of establishing sustainability governance within a newly formed mega-institution, which are real and should not be minimized. Its opportunities as a collection of unparalleled ecological narrative richness, a global audience of unprecedented scale, and a location whose landscape embodies five millennia of human-environment interaction are equally extraordinary. The question of whether the GEM will realize its potential as a platform for sustainability communication is one of the most consequential in the global museum sector, and one to which this research community should return as the institution's operational record develops.

The most enduring conclusion of this analysis is that sustainability and visitor experience are not competing values in museum scenographic practice, but are, when thoughtfully integrated, mutually reinforcing. The institutions that have made the greatest progress CalAcademy, NHM London, Naturalis are precisely those where sustainable practice has been embedded into the institution's deepest understanding of its own mission. As the museum sector confronts the dual challenges of the climate crisis and the global diversification of cultural infrastructure, this integration offers a compelling model for institutions of every scale, context, and tradition.

6.2 Limitations

This study has several limitations. The SSI scores are derived primarily from self-reported institutional data and published documentation rather than independent on-site measurement, which introduces the possibility of presentational bias. The sample of six institutions, while deliberately diverse, cannot be considered representative of the global museum sector. The scoring framework, developed with reference to professional and academic standards predominantly originating in high-income country contexts, may not fully capture sustainability achievements that are highly significant within lower-income country institutional environments. Future applications of the SSI should incorporate primary data collection and independent verification procedures.

6.3 Future Research Directions

Future research should pursue four principal directions. First, the SSI framework should be extended through application to a larger and more geographically diverse sample of institutions, including museums in South Asia, sub-Saharan Africa, and Latin America, where the intersection of cultural heritage, sustainability imperatives, and resource constraints presents particularly significant research opportunities. Second, context-adjusted SSI benchmarks for Global South institutions should be developed in collaboration with local museum professionals, ensuring that the framework evolves towards genuine global applicability. Third, longitudinal studies tracking the sustainability trajectories of recently opened mega-museums — including the GEM — would enable examination of how sustainability governance matures over institutional lifetimes. Fourth, quantitative methods including energy audit data and visitor behavioral surveys should be integrated with the qualitative comparative approach of this study to strengthen the empirical foundations of the SSI framework.

The most enduring conclusion of this analysis is that the museum, understood as a site of sustainability learning for both visitors and the institution itself, represents one of the most consequential arenas for the integration of design, technology, and environmental responsibility in contemporary cultural life. As the global museum sector confronts the dual challenges of the climate crisis and the diversification of cultural infrastructure towards the Global South, the integrated model proposed here offers a compelling and replicable vision for institutions of every scale, context, and tradition.

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Conflict of Interest

The authors declare that they have no conflicts of interest regarding the publication of this paper. The authors have no financial, professional, or personal relationships that could have appeared to influence the work reported in this study.

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