buildings

MDPI

Article

Developing a Climate-Referenced SS–LT Site-Performance Assessment Framework: An Exploratory Five-Case Study of Green-Certified Smart Office Buildings

Ezgi Yılmaz [1,*] and Mehmet Sair Akkam [2]

[1] Faculty of Architecture, Istanbul Aydın University, Istanbul 34295, Türkiye
[2] Faculty of Engineering and Architecture, İstanbul Gelişim University, Istanbul 34520, Türkiye; msakkam@gelisim.edu.tr
* Correspondence: ezgiyilmaz@aydin.edu.tr

Abstract

Green-building research has examined energy efficiency and indoor environmental quality in depth, whereas site-related strategies are often represented through aggregate certification outcomes with limited visibility into criterion-level evidence and weighting assumptions. This study develops the Climate-Referenced SS–LT Site-Performance Assessment Framework (CR-SSAF) for an exploratory documentation-based comparison of a combined Sustainable Sites, Location, and Transportation (SS–LT) construct across five green-certified smart office buildings in three Köppen climate zones. Six SS–LT criteria were assessed using a four-level operational rubric, an exact-normalized weighted Site-Performance Index (SSPI), a descriptive Technology Enablement Factor (TEF), ordinal inter-rater agreement analysis, three weighting schemes, and a TOPSIS ranking-concordance check. SSPI values ranged from 2.00 to 2.65. The Af case recorded the highest SSPI in this sample, while the lowest scores occurred where no qualifying project-specific heat-mitigation or green-/open-space evidence could be verified. The first, second, and last ranks remained unchanged across the three weighting schemes, while The Edge and Shanghai Tower were tied under the equal and ecology-sensitive schemes. Because the sample is small and heterogeneous, and does not control for urban form, building scale, infrastructure, certification system, or documentation availability, differences cannot be attributed independently to climate. CR-SSAF is therefore presented as a transparent exploratory workflow, not as a validated climate effects model or as evidence of transferability.

Keywords: Sustainable Sites (LEED); Location and Transportation (LEED); climate-referenced assessment; green building certification; smart office buildings; exploratory case-study research; multi-criteria assessment

Check for updates

Academic Editor: Xing Jin

Received: 30 June 2026
Revised: 11 August 2026
Accepted: 14 August 2026
Published: 16 August 2026

1. Introduction

The building sector accounts for approximately 40% of global energy consumption and 36% of energy-related carbon emissions, making its environmental performance a major challenge for sustainable urban development [1–3]. Consequently, improving the sustainability of office buildings has become a strategic priority for governments, designers, and certification bodies seeking to reduce environmental impacts while maintaining occupant well-being. In this context, smart building technologies—including building management systems (BMSs), sensor-based controls, real-time monitoring, and artificial intelligence (AI)-driven optimization—have emerged as key enablers of sustainable building operation.

Beyond reducing energy consumption, these technologies improve operational efficiency, enhance occupant comfort, and support broader environmental and socio-economic sustainability objectives [4–6].

Among sustainability assessment systems, LEED provides a widely used and explicitly structured set of credits covering energy, water, indoor environmental quality, materials, Sustainable Sites (SS), and Location and Transportation (LT) [2,7]. In this study, selected LEED v4 SS and LT credit logic is used only to derive a common study-specific instrument. Certification labels and scores from LEED, BREEAM, and BCA Green Mark are not converted or directly compared.

Despite extensive research on energy efficiency and indoor environmental quality, less attention has been paid to criterion-level patterns in documented SS–LT strategies across climatic contexts. Existing studies often focus on a single climate or on aggregate certification outcomes, making it difficult to inspect which site strategies are documented in each case and how comparative results depend on evidence rules and weighting assumptions. The gap addressed here is therefore methodological: a transparent workflow for comparing a combined SS–LT construct while treating climate as contextual rather than causal.

To address this methodological gap, the study develops and demonstrates CR-SSAF as an exploratory documentation-based workflow for comparing a combined SS–LT construct across cases situated in different climatic and institutional contexts. Six criteria derived from selected LEED v4 SS and LT credit logic are assessed through the SS–LT Site-Performance Index (SSPI), while documented smart-operational capabilities are reported separately through a descriptive Technology Enablement Factor (TEF). The workflow is demonstrated using Bloomberg London, The Edge, Bank of America Tower, Shanghai Tower, and CapitaGreen; it is not designed to estimate an independent climate effect.

The following section illustrates the sequential methodological workflow adopted in this study. The workflow begins with criteria extraction of the selected SS–LT criteria, followed by criterion-based case selection and operational scoring of SS1–SS6 and of the smart-technology indicators retained after evidence verification (ST1–ST2). Index calculation and sensitivity analysis are then applied to derive the SS–LT Site-Performance Index (SSPI) and the Technology Enablement Factor (TEF), together with weighting-scenario checks. The workflow concludes with analytical checks and a five-case demonstration, including inter-rater agreement and a TOPSIS ranking-concordance check, to examine whether the proposed scoring workflow can be applied consistently across different climatic and institutional contexts.

Building upon this methodological framework, the following research questions and study contributions define the scope and scientific objectives of the present research.

The methodological novelty is the integration of an explicit SS–LT rubric, a project-level evidence trail, independent ordinal scoring, and transparent weighting-sensitivity and ranking-concordance checks within one exploratory workflow.

1.1. Research Questions

To address the identified research gap, this study investigates the following research questions:

RQ1: What criterion-level site-performance patterns are observed across five green-certified smart office buildings located in three Köppen climate zones?

RQ2: How are documented smart building technologies represented within the proposed site-performance assessment workflow?

RQ3: How sensitive are the comparative building rankings to alternative criterion weights?

The relationship between these research questions and the analytical workflow is summarized as follows:

RQ1 is addressed through the Site-Performance Matrix and cross-case comparison (Sections 3.1 and 4.1);

RQ2 is examined through the Smart Building Technology Matrix and the Technology Enablement Factor (TEF) (Sections 3.2, 3.3 and 4.4);

RQ3 is investigated through weighting-based sensitivity analysis and the TOPSIS ranking-concordance check (Sections 3.4 and 4.3).

1.2. Contributions

This study makes three bounded methodological contributions:

A criterion-level operationalization: Six selected SS/LT credit logics are translated into explicit 0–3 documentary evidence rules.

An auditable evidence record: All 40 rater decisions, confidence metadata, source identifiers, and scoring rationales are reported in the Supplementary Materials.

An assumption-explicit comparison: Three normative weight sets and a TOPSIS concordance check show how rankings depend on model choices without treating those checks as validation.

Together, these elements provide a protocol for subsequent larger-sample testing rather than evidence of framework validity or transferability.

2. Materials and Methods

This section first describes the selected buildings and their climatic profiles, then explains—step by step—how the Climate-Referenced SS–LT Site-Performance Assessment Framework (CR-SSAF) was developed, operationalized, and demonstrated. CR-SSAF is specified in sufficient detail for future re-application and testing by other researchers; its transferability to other samples, building typologies, and certification contexts is not established in the present study.

2.1. Scientific Rationale and Case Selection

The development of the proposed Climate-Referenced SS–LT Site-Performance Assessment Framework (CR-SSAF) is grounded in three complementary research domains: sustainable building certification, climate-responsive building assessment, and smart building technologies. Together, these domains establish the scientific rationale for selecting the case studies and defining the methodological structure adopted in this research.

LEED v4 was selected as the criterion-extraction reference because it provides explicit SS and LT credit structures that can be translated into a common study-specific rubric [2,7]. Other systems—including BREEAM, DGNB, Green Star, CASBEE, and BCA Green Mark—differ in weighting, regional priorities, and assessment procedures [2,8]. These differences are not treated as equivalent certification outcomes in CR-SSAF: certification status is used only as a case-selection filter, and every case is reassessed using the same rubric. Prior work showing that certification points do not necessarily correspond to climatic environmental outcomes further supports separating documentary site-strategy scoring from claims about measured performance [9,10].

Climatic context is relevant to the interpretation of building strategies, but relevance does not by itself establish a causal climate effect. Pérez-Lombard et al. [1] and Reinhart and Davila [11] demonstrate the importance of climate for building energy performance, while Greer et al. [10] show that LEED points are not consistently associated with climatic energy and water outcomes. The present study therefore examines documented SS–LT strategy patterns alongside climate descriptors without interpreting the rubric scores as environmental outcomes or the climatic descriptors as moderators. This distinction provides the scientific rationale for a climate-referenced, rather than climate-adjusted, framework.

Recent developments in IoT, digital twins, and intelligent building management systems have expanded the role of smart technologies in building operation [4,12–15]. Because the available project documentation did not support direct estimation of environmental benefit, CR-SSAF records these capabilities separately from SSPI. The TEF therefore represents only the documented scope of building management and sensor systems retained after evidence verification; it is not an estimate of technology's contribution to site performance or measured environmental outcomes.

The representative studies summarized in Table 1 cover certification-system comparison, scoring and ranking methods, reusable assessment matrices, certified-building evidence, and smart building technologies [6,8–10,12–20]. Within this bounded comparison, the reviewed studies do not combine a study-specific SS–LT rubric, project-level evidence tracing, ordinal inter-rater scoring, explicit weight sensitivity, and a same-data ranking-concordance check in one workflow. Table 1 therefore positions the methodological combination proposed here; it is not a systematic-review basis for claiming absolute priority or that CR-SSAF is the first framework of its kind.

Table 1. Research Gap Matrix: Comparison of representative studies.

Study	Climate Integration	Smart Technology	SS–LT/Site Assessment	Weighted Framework	Sensitivity Analysis	Operational Protocol Specified
Greer et al. [10]	Partial	No	Yes	No	No	No
Ismaeel [19]	No	No	Partial	No	No	No
Zarghami & Ahmad [9]	Partial	No	No	No	No	No
Tahmasebinia et al. [12]	No	Yes	No	No	No	No
Bibri and Huang [14]	No	Yes	No	No	No	No
Oulefki et al. [13]	No	Yes	No	No	No	No
Cespedes-Cubides & Jradi [15]	Partial	Yes	No	No	Partial	Partial
This Study (CR-SSAF)	Contextual/ descriptive	Yes	Yes	Yes	Yes	Yes

This study examines five internationally recognized green-certified smart office buildings representing three Köppen climate contexts (two Cfb, two Cfa, one Af). The basic profile of the buildings is summarized in Table 2.

Table 2. Characteristics of the five green-certified smart office buildings selected as case studies for the CR-SSAF five-case demonstration and the case-selection criteria applied to the five buildings. Project characteristics were compiled from the official and institutional project sources listed in References [21–26] and Supplementary Table S5.

Building	Scale (Floor Area; Height/Floors)	Certification System	Key Smart Building Features	Köppen Climate
Bloomberg London	≈102,000 m^2 (1.1 million ft^2); 10 storeys, low-rise urban complex	BREEAM Outstanding	Integrated ceiling system, responsive HVAC control, daylight-responsive lighting, BMS	Cfb
The Edge (Amsterdam)	≈40,000 m^2; 15 storeys	BREEAM Outstanding	≈28,000 sensors, ATES, rooftop PV, rainwater harvesting	Cfb

Table 2. *Cont.*

Bank of America Tower	≈195,000 m^2 (2.1 million ft^2); 55 storeys	LEED Platinum	Building automation, energy-recovery HVAC, multi-parameter air monitoring	Cfa
Shanghai Tower	≈578,000 m^2; 632 m, 127 above-ground floors	LEED Platinum (C&S)	Double-skin façade, facility-network automation, wind turbines	Cfa
CapitaGreen	≈82,000 m^2; 40 storeys	BCA Green Mark Platinum	Wind scoop, vertical greenery, sensor-controlled lighting and HVAC zoning	Af

Selection Criterion	**Bloomberg London**	**The Edge**	**Bank of America Tower**	**Shanghai Tower**	**CapitaGreen**
Office typology	✓	✓	✓	✓	✓
Highest-tier certification in own system	✓	✓	✓	✓	✓
Smart technologies documented	✓	✓	✓	✓	✓
Site-related evidence available	✓	✓	✓	✓	✓
Köppen climate context	Cfb	Cfb	Cfa	Cfa	Af

Note: ✓ indicates that the case satisfies the corresponding selection criterion.

The case studies were selected using a purposive (criterion-based) sampling strategy [27], combining qualitative and quantitative evaluation within a comparative multiple-case design. Buildings were selected to satisfy five conditions: (i) internationally recognized, highest-level green certification (LEED Platinum or the highest level of an equivalent national system); (ii) office (commercial) typology; (iii) documented integration of smart building technologies; (iv) sufficient technical documentation to support criterion-based scoring; and (v) collective representation across multiple Köppen climate zones. Importantly, this study does not compare certification systems against one another; rather, it compares site-performance strategies in buildings that have reached the highest available sustainability certification within their own certification system and context. BREEAM Outstanding and BCA Green Mark Platinum are treated as context-specific proxies for "top-tier sustainability performance," not as scores equivalent to LEED Platinum. These criteria ensure methodological consistency while assembling an information-rich comparative sample; they were not designed to isolate or estimate the independent statistical effect of climate. The five-case sample was deliberately structured as an information-rich methodological demonstration rather than as a statistically representative or climate-balanced sample. It was limited to projects that met the stated selection filters and provided sufficient project-specific evidence for criterion-level assessment. The 2–2–1 distribution across Cfb, Cfa, and Af therefore reflects evidence availability rather than balanced climate-zone sampling.

Certification labels were used only as case-selection filters indicating internationally recognized high-performance projects; original certification scores were neither converted nor directly compared against one another. All five buildings were independently re-assessed using the same study-specific SS–LT criteria, scoring thresholds, and evidence requirements described in Section 2.3, so the comparative results reported in Section 3 rest on a single common instrument rather than on the certification systems' own scoring rules. Nevertheless, differences in certification documentation and reporting conventions across LEED, BREEAM, and BCA Green Mark remain a potential source of evidence bias, since projects are not equally well documented in the public record.

The cases were not selected to isolate or estimate the independent effect of climate. They constitute a criterion-based, information-rich sample used to demonstrate whether the proposed scoring workflow can be applied to buildings located in different climatic and institutional contexts. Consequently, cross-case differences may also reflect urban morphology, building scale, transport infrastructure, certification background, and the quantity and quality of publicly available documentation. The study therefore seeks analytical and methodological insight rather than statistical generalization.

Following the visual overview presented in Figure 1, the principal sustainability characteristics of each case-study building are briefly summarized below.

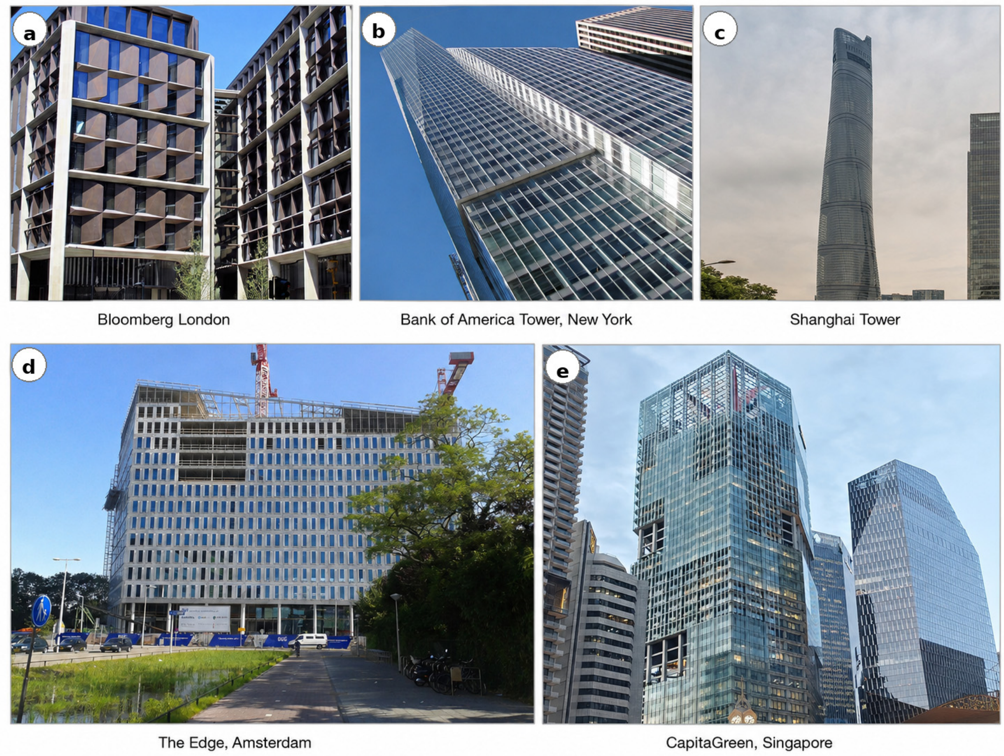

Figure 1. Representative exterior views of the five green-certified smart office buildings included in the CR-SSAF exploratory case-study demonstration: (**a**) Bloomberg London; (**b**) Bank of America Tower, New York; (**c**) Shanghai Tower; (**d**) The Edge, Amsterdam; and (**e**) CapitaGreen, Singapore. Image sources: (**a**) David Holt, Bloomberg European Headquarters, London, CC BY 2.0; (**b**) Eden, Janine and Jim, One Bryant Park (8156006545), CC BY 2.0; (**c**) xiquinhosilva, Shanghai Tower (32910112532), CC BY 2.0; (**d**) Han Jongeneel, The Edge—panoramio, CC BY 3.0; and (**e**) DvTor8303, CapitaGreen Tower 20250904, CC0 1.0; all via Wikimedia Commons [28–32]. The photographs were cropped, resized, labeled, and assembled by the authors for consistent panel presentation.

Bloomberg London is a BREEAM Outstanding-certified office complex for which the reviewed sources document an integrated ceiling system, responsive HVAC controls, daylight-responsive lighting, cycling provision, and rainwater and greywater reuse [21,22]. No qualifying project-specific green roof or exterior heat-mitigation strategy was verified in the evidence set used for scoring.

Bank of America Tower (One Bryant Park) is a LEED Platinum-certified high-rise office building for which the reviewed sources document high-performance glazing, energy-recovery HVAC, building automation, rainwater harvesting, greywater reuse, green-roof interventions, and public ground-level space [23,33]. Only evidence corresponding to the study-specific SS1–SS6 and ST1–ST2 thresholds was used in the assessment.

Shanghai Tower is a supertall mixed-use building certified as LEED Platinum (Core and Shell) and as a 3-Star China Green Building. The reviewed project sources document a double-skin façade, sky gardens, greywater/rainwater systems, facility-network automation, environmental monitoring, and multimodal transport connections [24,34]. These documented features were scored without inferring operational environmental outcomes.

The Edge is a BREEAM Outstanding-certified office building for which the reviewed sources document an extensive sensor network, app-based controls, aquifer thermal energy storage, photovoltaic systems, rainwater reuse, cycling provision, and green terraces [26,35]. The building's smart-operational systems and SS–LT strategies were assessed separately through TEF and SSPI.

CapitaGreen is the single Af (tropical rainforest) case in the sample and is certified under Singapore's BCA Green Mark Platinum system. The reviewed sources document vertical greenery, multi-level sky terraces, a wind scoop, rainwater harvesting, sensor-controlled lighting, HVAC zoning, and access to MRT and cycling facilities [25,36]. These are treated as documented strategies rather than measured evidence of climatic effectiveness.

Although these buildings differ in architectural form, certification systems, and technological solutions, they all represent internationally recognized examples of high-performance smart office buildings. Together, these characteristics establish an information-rich basis for demonstrating the workflow and climate referencing of the proposed CR-SSAF.

Given that climatic context constitutes a descriptive contextual variable within the proposed Climate-Referenced SS–LT Site-Performance Assessment Framework (CR-SSAF), the long-term climatic characteristics of the five case-study locations were compiled using the Köppen–Geiger climate classification together with representative meteorological indicators. Table 3 summarizes these climatic profiles and provides the environmental baseline for interpreting cross-case patterns in relation to climatic context on combined SS–LT site performance.

Table 3. Climatic profile of the five buildings (Köppen–Geiger; long-term means). Köppen–Geiger classifications were derived from Beck et al. [37]; temperature and rainfall values were compiled from KNMI (Amsterdam) [38]; NOAA (New York) [39]; CMA (Shanghai) [40]; Meteorological Service Singapore [41]; and UK Met Office (London) [42].

Building/City	Köppen	Mean Annual T	Annual Rainfall	Climate Type
Bloomberg London/London	Cfb	~10.8 °C	~690 mm	Temperate oceanic
The Edge/Amsterdam	Cfb	~10.7 °C	~840 mm	Temperate oceanic (maritime)
Bank of America Tower/New York	Cfa	~13 °C	~1250 mm	Humid subtropical
Shanghai Tower/Shanghai	Cfa	~16.6 °C	~1200 mm	Humid subtropical (monsoonal)
CapitaGreen/Singapore	Af	~27 °C	~2340 mm	Tropical rainforest

The five buildings differ by about 3.4-fold in rainfall (690–2340 mm) and by 16 °C in mean annual temperature (10.7–27 °C), spanning three Köppen climate zones (Cfb, Cfa, Af). The selected case studies exhibit substantial variation in long-term climatic conditions, ranging from temperate oceanic to tropical rainforest climates. This climatic diversity provides a broad descriptive context for interpreting cross-case differences in combined SS–LT site performance, though with only three climate zones and five cases it does not permit statistical isolation of a climate effect.

2.2. CR-SSAF Framework Overview

CR-SSAF's development comprises five stages: (1) criteria extraction and literature grounding; (2) case selection; (3) scoring rubric and weighting; (4) inter-rater agreement checking; and (5) sensitivity analysis and TOPSIS ranking-concordance checking. CR-SSAF consists of four integrated measurement modules: Module 1—Site-Performance Matrix (six SS–LT criteria, SS1–SS6, and the four-level 0–3 Master Operational Scoring Rubric); Module

2—Site-Performance Index (SSPI); Module 3—Technology Enablement Factor (TEF); and Module 4—Sensitivity and Analytical-Checks Layer (TOPSIS ranking-concordance check, three-scheme weighting sensitivity, and inter-rater agreement). Its application is presented in Section 3.

The overall methodological workflow is illustrated in Figure 2, while Box 1 summarizes the practical implementation procedure.

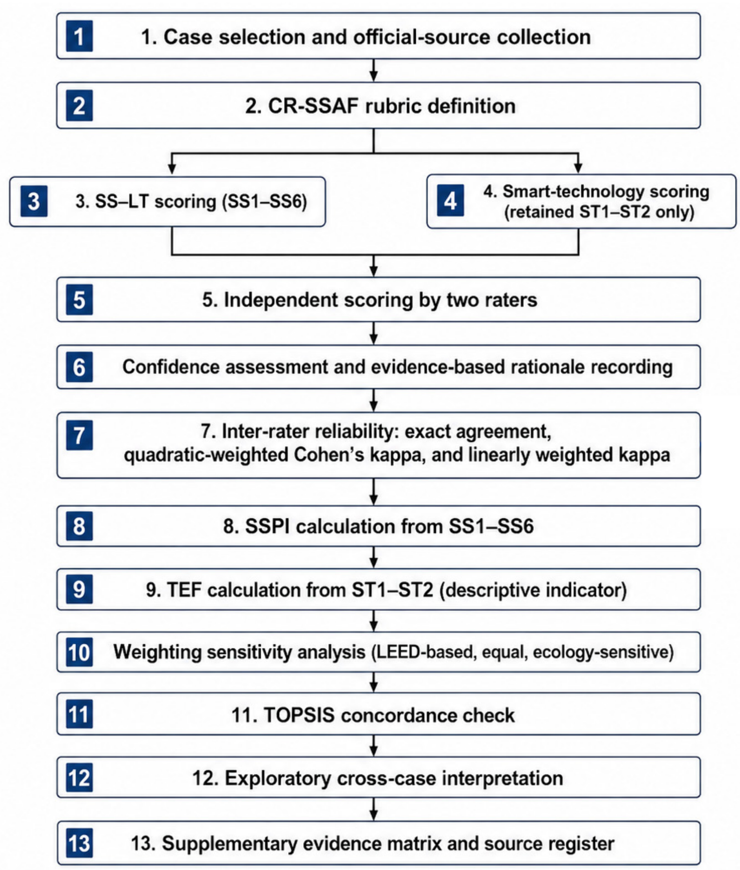

Figure 2. Methodological workflow of the CR-SSAF, comprising case selection and official-source collection; definition of the operational scoring rubrics for the SS–LT criteria (SS1–SS6) and the retained smart-technology indicators (ST1–ST2); independent scoring, confidence assessment, and inter-rater reliability analysis; calculation of the SS–LT Site-Performance Index (SSPI) and the descriptive Technology Enablement Factor (TEF); weighting-sensitivity analysis and a TOPSIS ranking-concordance check; and exploratory cross-case interpretation supported by the supplementary evidence matrix and source register.

Box 1. CR-SSAF was implemented through five sequential steps.

1. Criteria extraction: derive six SS–LT site-performance criteria (SS1–SS6) from selected LEED v4 SS/LT credit logic.
2. Case selection: build a criterion-based purposive sample using explicit selection filters (Table 2).
3. Operational scoring: score each criterion using the Master Operational Scoring Rubric (Section 2.3) and the smart-technology rubric (Section 2.4), retaining only those technology indicators for which a project-specific documentary source can be cited.
4. Weighting and indexing: compute SSPI under the three weighting schemes (Section 2.5) and TEF over the retained smart-technology indicators.
5. Analytical checks: apply inter-rater agreement (Cohen's kappa), the TOPSIS ranking-concordance check, and weighting-sensitivity analysis.

This sequence documents the procedure for future re-application and testing; it does not establish transferability or a climate-effect model.

2.3. Criteria Extraction and Operational Rubric

To strengthen analytical rigour, a Climate–Site Performance Assessment Matrix was developed on the basis of LEED v4 BD + C credit logic. Because the study examines the building's relationship with its urban site, the matrix deliberately spans two adjacent LEED categories—Sustainable Sites (SS) and Location and Transportation (LT)—integrating the credits that jointly determine site quality (Table 4) [7]. The CR-SSAF rubric is a study-specific ordinal operationalization informed by selected LEED v4 SS and LT credit logic; it does not reproduce LEED certification thresholds or constitute an alternative certification scorecard.

Table 4. Site-performance criteria and their LEED v4 credit bases.

Code	Assessment Criterion	LEED v4 Basis
SS1	Site selection	Site Assessment; Sensitive Land/High-Priority Site
SS2	Urban connectivity	Surrounding Density and Diverse Uses (LT)
SS3	Alternative transportation	Access to Quality Transit; Bicycle Facilities (LT)
SS4	Open space provision	Open Space (SS)
SS5	Rainwater management	Rainwater Management (SS)
SS6	Heat-mitigation strategies	Heat Island Reduction (SS)—study-specific adapted operationalization

Because the public project documentation did not consistently report the solar-reflectance-index values, nonroof-area calculations, or other metrics required for formal LEED Heat Island Reduction assessment, SS6 was operationalized as a study-specific exterior heat-mitigation criterion. A vegetative, shading, surface, or façade/envelope measure was counted only when a project-specific source explicitly documented the measure and linked it to solar-control, thermal, or heat-island intent. Each distinct strategy was counted once; related components of the same system were not counted separately. SS6 should therefore not be interpreted as a reproduction of the formal LEED credit or as measured thermal performance.

Each criterion was evaluated on the four-level (0–3) Master Operational Scoring Rubric shown in Table 5. The revised rules distinguish score levels through countable documentary components or explicit project conditions. A score records the highest threshold fully supported by the frozen evidence package; undocumented components are not inferred, and score 0 denotes absence of qualifying evidence in the reviewed record rather than confirmed real-world absence. Project-level evidence was collected and verified up to 3 August 2026 using a predefined source hierarchy. Certification bodies and public authorities were prioritized, followed by project owners and developers, design and engineering teams, recognized institutional databases, and peer-reviewed literature where project-specific information was available. A score was assigned only when at least one project-specific source explicitly supported the relevant rubric threshold. Where evidence was incomplete, ambiguous, or conflicting, the highest score fully supported by the available record was assigned; undocumented components were not inferred. The finalized evidence package was frozen before independent scoring and is reported in Supplementary Tables S2 and S5.

Table 5. Master Operational Scoring Rubric for SS1–SS6 and expected evidence types. Score levels are defined through explicit documentary conditions or component counts; operational definitions for SS1, SS2, SS3, and SS6 follow in the table.

Criterion	Score 0	Score 1	Score 2	Score 3	Evidence Type Expected
SS1 Site selection	No qualifying project-specific evidence was identified in the reviewed sources.	Standard urban/infill site.	Infill site plus one documented ecological intervention (e.g., native/climate-tolerant planting, green roof/façade, or on-site greening), without explicit habitat restoration.	Infill site plus explicit project-specific evidence of habitat or ecological restoration.	Site plan or certification narrative describing prior land use and any ecological measures.
SS2 Urban connectivity	No qualifying project-specific evidence was identified in the reviewed sources.	One of three components is documented: density, mixed-use diversity, or walkable access to urban functions.	Two of the three components—density, mixed-use diversity, and walkable access—are explicitly documented.	All three components—density, mixed-use diversity, and walkable access to at least two urban functions or a major transport node—are explicitly documented.	Urban-context description or certification documentation of surrounding density/uses.
SS3 Alternative transportation	No qualifying project-specific alternative-transport evidence was identified.	One documented transit service/connection or one active-mobility or reduced-parking measure.	At least two separately documented transit services/connections, but no documented cycling/end-of-trip or reduced-parking measure.	At least two separately documented transit services/connections plus at least one cycling/end-of-trip or reduced-/zero-parking measure.	Transit-access documentation or certification narrative on modal access.
SS4 Open space	No qualifying project-specific open-space evidence was identified.	Public realm/open space is documented, but access is restricted or no green component is documented.	Accessible green/open space is documented at one principal location or level, but not across multiple exterior levels.	Accessible green/open space is documented at ground and roof levels or across at least two exterior building levels.	Site plan, floor plan, or certification documentation quantifying open space.
SS5 Rainwater management	No qualifying project-specific evidence was identified in the reviewed sources.	Retention only.	Retention + reuse.	Retention + reuse + sensor-based monitoring.	Technical documentation of stormwater/rainwater systems.
SS6 Heat-mitigation strategies	No qualifying project-specific evidence was identified in the reviewed sources.	One distinct documented exterior heat-mitigation strategy.	Two distinct documented exterior heat-mitigation strategies.	Three or more distinct documented exterior heat-mitigation strategies.	Certification documentation or technical description of roof/site heat-mitigation measures.

For SS1, a score-2 ecological intervention required explicit evidence of at least one on-site greening or planting measure, whereas score 3 required explicit habitat or ecological restoration. For SS2, density was accepted only when an official planning, certification, or project source described the context as dense or high-density; mixed-use diversity required documented non-office uses; and walkable access required documented pedestrian access to at least two urban functions or a major transport node. For SS3, each separately named transit line, mode, station, or direct connection counted as one service/connection; cycling facilities, showers/end-of-trip provision, and reduced or zero parking counted as active-mobility or demand-management measures. For SS6, only distinct documented exterior strategies were counted, with related components of one system counted once.

https://doi.org/10.3390/buildings16163247

2.4. Smart Building Technology Assessment

A second matrix was developed to record smart operational capabilities potentially relevant to site performance. Five candidate indicators were initially specified, but project-specific evidence across all five cases was available only for ST1 (building management systems) and ST2 (environmental sensors). Table 6 therefore presents indicator-specific documentary thresholds based on the number of linked building systems, the number of monitored variables, and whether project-wide or building-wide scope is explicitly documented. ST3–ST5 remain listed as a specification for future applications but were unscored and excluded from the TEF because their inclusion would have required inference.

Table 6. Smart building technology indicators related to site performance and indicator-specific operational scoring rules for ST1 and ST2. Thresholds are based on documented system count, sensor-variable count, and network scope; ST3–ST5 were not scored.

Code	Technology Indicator	Relationship to Site Performance
ST1	Building management systems	Operate site systems (lighting, HVAC, water) efficiently.
ST2	Environmental sensors	Monitor microclimate, air, and site conditions in real time.
ST3	Smart water monitoring	Sensor-driven control of rain/greywater harvesting and reuse.
ST4	Smart mobility integration	Low-carbon access and transport-demand management.
ST5	Data-driven site management	Analytics/IoT-based landscape and open-space management.
Score	**Description (Applies to ST1–ST2)**	
0	No qualifying project-specific evidence was identified in the reviewed sources.	
1	ST1: automation of one building system. ST2: one sensor type or monitored variable.	
2	ST1: at least two automated or linked building systems, but no documented project-wide platform. ST2: at least two sensor types/variables or zone-based sensing linked to control, but no documented building-wide multi-parameter network.	
3	ST1: a documented project-wide platform linking at least three building systems and supporting real-time control or analytics. ST2: a documented building-wide network monitoring at least three environmental/occupancy variables and supporting real-time control or analytics.	

2.5. Weighted Performance Analysis

The primary weighting scheme was constructed as a LEED-informed normative baseline rather than as a reproduction of a formal LEED project scorecard. Because several CR-SSAF criteria combine the logic of more than one LEED credit, one representative point value was assigned to each composite criterion instead of summing all linked credit maxima, thereby avoiding double counting. The representative values used for SS1–SS6 were 2, 5, 5, 1, 3, and 1, respectively. For SS6, the lower formal point value was used conservatively because the study-specific heat-mitigation criterion extends beyond the formal LEED Heat Island Reduction credit to include broader shading and envelope strategies. These values provide a transparent baseline, while the equal and ecology-sensitive schemes test how strongly the findings depend on that normative choice. Weights were normalized to sum to 100% (Table 7).

Table 7. Criterion weights under the three weighting schemes used in the sensitivity analysis. The LEED-informed baseline percentages are displayed to two decimals, while calculations use the exact normalized fractions. The ecology-sensitive scheme is a hypothetical sensitivity scenario, not an empirically validated weighting model.

Criterion	LEED-Informed Baseline	Equal	Ecology-Sensitive
SS1 Site selection	11.76%	16.67%	10%
SS2 Urban connectivity	29.41%	16.67%	15%
SS3 Alternative transportation	29.41%	16.67%	15%
SS4 Open space	5.88%	16.67%	20%
SS5 Rainwater management	17.65%	16.67%	25%
SS6 Heat-mitigation strategies	5.88%	16.67%	15%
Total	100%	100%	100%

The ecology-sensitive scheme was introduced solely as a hypothetical sensitivity scenario. It assigns 60% of the total weight to the three ecological criteria (SS4–SS6), compared with 30% for connectivity and transportation (SS2–SS3) and 10% for site selection (SS1). The scheme is not proposed as an empirically validated or universally applicable weighting model; it is used only to test how sensitive the comparative rankings are to a plausible alternative set of normative priorities.

The LEED-informed baseline weights were obtained by normalizing the selected raw values 2, 5, 5, 1, 3, and 1 over a total of 17. The exact weights—2/17, 5/17, 5/17, 1/17, 3/17, and 1/17—were used in every SSPI and TOPSIS calculation; percentages in Tables 7 and 8 are displayed to two decimals. Equal-weight calculations used exactly 1/6 per criterion.

Table 8. Completed site-performance scores (0–3) for the five buildings. Each score rests on the Table 5 protocol and on two independently recorded rater scores that agreed exactly on all decisions (Section 2.7). Per-item evidence, source identifiers and scoring rationales are reported in Supplementary Table S2.

Code	Criterion	Wt.	Bloom.	Edge	BoA	Shanghai	Cap.
SS1	Site selection	11.76%	1	2	2	2	2
SS2	Urban connectivity	29.41%	2	3	3	3	3
SS3	Alt. transportation	29.41%	3	3	3	2	3
SS4	Open space	5.88%	1	2	2	2	3
SS5	Rainwater mgmt.	17.65%	2	2	2	2	2
SS6	Heat mitigation	5.88%	0	1	2	2	2

For each building, the SS–LT Site-Performance Index (SSPI) is computed as the weighted sum of the criterion scores (Equation (1)):

$$\mathrm{SSPI} = \Sigma\,(w_i \times s_i),\ i = 1\ldots6 \tag{1}$$

where w_i is the normalized weight of criterion i (Table 7) and s_i is its 0–3 rubric score. Because the weights sum to one and the maximum score is 3, SSPI is bounded in 0–3. A Technology Enablement Factor (TEF) was defined as the mean of the two scored smart-technology indicators (ST1–ST2), normalized to 0–1 (Equation 2). The three indicators withdrawn for lack of project-specific documentation (ST3–ST5, Section 2.4) do not enter the denominator, so TEF here measures documented smart operational capability rather than the full technology construct originally specified:

$$TEF = (\Sigma\, t_j)/6,\ j = 1\ldots 2 \quad (2)$$

2.6. Climate and Site-Performance Contextual Interpretation

Climatic context was used as a descriptive interpretive lens rather than as a statistically tested moderator or causal variable. Criterion-level differences were examined alongside Köppen classifications and long-term temperature and rainfall data; however, the design does not isolate climate from urban morphology, building scale, infrastructure, certification background, or documentation availability. Accordingly, the framework identifies cross-case patterns for subsequent testing rather than estimating climate effects. Mean annual temperature, annual rainfall, and Köppen–Geiger classification were retained only as comparable descriptive climate descriptors and were not combined into a climate-severity index. Relative humidity, solar radiation, wind conditions, heating and cooling degree-day metrics, and extreme-event indicators were excluded because comparable project-linked data were not consistently available across all five locations and the present five-case design could not estimate their independent effects. Their exclusion limits the climatic interpretation, which remains contextual rather than operational or causal.

2.7. Inter-Rater Agreement and Analytical Checks

Because scoring in a documentation-based study rests on judgement, measures taken to support consistency included cross-checking of certification documentation against academic publications, source verification against official building/developer sources where possible, and rule-based scoring following the Table 5 protocol. Each score was evaluated against the operational rubric and linked to the documentary evidence available for the relevant case; evidence completeness and limitations are reported in Supplementary Tables S2 and S5. Two researchers independently recorded scores for the six SS–LT criteria and the two retained smart-technology indicators across the five buildings (40 decisions: 30 SS–LT and 10 ST1–ST2). The two score sets were completed separately and compared before any consensus entry. Exact agreement was obtained on all 40 decisions (observed agreement $p_o = 1.00$), with quadratic-weighted Cohen's $\kappa = 1.000$ and linearly weighted $\kappa = 1.000$; no adjudication was required. Quadratic-weighted kappa is reported as the primary statistic because the scale is ordinal, with exact agreement and linear weighting as supplementary checks; kappa magnitudes are interpreted against the benchmarks proposed by Landis and Koch [43], and the underlying documentary coding procedure follows established practice in systematic content analysis [44]. Reliability was computed in an Excel-compatible contingency-matrix workbook using explicit quadratic and linear weighting formulas; the completed calculation workbook and the two rater workbooks are provided as Supplementary Data. Rater-level scores, per-item confidence ratings and the full agreement matrices are reported in Supplementary Tables S3 and S4. Per-rater confidence was recorded as audit metadata and was not entered into the kappa calculation; the ten items on which the two raters recorded the same score but different confidence levels are listed in Supplementary Table S3. Accordingly, the present study supports procedural reliability and limited content grounding, not comprehensive framework validity. Content grounding derives from the selected LEED v4 SS–LT credit logic and the source-linked project evidence. Construct, criterion, predictive, and external validity remain untested. Weighted kappa evaluates only the consistency of rubric application, while TOPSIS provides only an internal ranking-concordance check because it uses the same underlying scores and weights.

2.8. Multi-Criteria Ranking: TOPSIS

TOPSIS (Technique for Order of Preference by Similarity to Ideal Solution) [17] was applied as a ranking-concordance check rather than as an independent validation method, since it is computed from the same underlying scores and the same LEED-informed baseline weights as the SSPI. The method comprises vector normalization of the decision matrix, multiplication by the LEED-informed baseline weights, computation of distances to the positive- and negative-ideal solutions, and the relative closeness coefficient (Ci*). The results are presented in Section 3.5.

2.9. Use of Generative Artificial Intelligence

During the preparation and revision of this manuscript, ChatGPT (OpenAI, GPT-5.6 Sol, web version; accessed in August 2026) was used to support language refinement, consistency checks, formatting assistance, and the preparation of draft graphical layouts. The tool was not treated as an independent documentary source. All source selection, evidence verification, scoring decisions, calculations, interpretations, and final manuscript content were reviewed and approved by the authors.

3. Results

The proposed Climate-Referenced SS–LT Site-Performance Assessment Framework (CR-SSAF) was applied to the five selected case-study buildings following the methodology described in Section 2. Site-performance (SS1–SS6) and smart-technology (ST1–ST2) indicators were evaluated by two independent raters using the standardized operational protocol presented in Table 5 (quadratic-weighted Cohen's $\kappa = 1.000$ across 40 decisions; Section 2.7 and Supplementary Tables S3 and S4). Each score was evaluated against the operational rubric and linked to the documentary evidence available for the relevant case; evidence completeness and limitations are reported in Supplementary Tables S2 and S5. The following subsections present the completed assessment matrices, weighted performance indices, sensitivity analyses, ranking-concordance results and cross-case criterion-level patterns identified across the five case studies.

3.1. Site-Performance Matrix—Completed Scores (RQ1)

The first assessment stage assigned scores to the six SS–LT criteria using the predefined operational rubric. Two raters recorded the 30 ordinal SS–LT decisions independently before comparison; Table 8 reports the common scores, and Supplementary Tables S2–S4 report the evidence trail, confidence metadata, and agreement results.

The completed Site-Performance Matrix constitutes the primary dataset for all subsequent weighted analyses. Overall, the results reveal two distinct patterns: comparatively uniform scores on alternative transportation (SS3 = 2–3 in every case) and on rainwater management (SS5 = 2 in every case), and substantially greater cross-case variation in the remaining ecological criteria, with open space (SS4) and heat mitigation (SS6) showing the widest cross-case variation, each spanning a two-point range.

Examples of decisive evidence: CapitaGreen SS4 = 3 (55% green ratio, multi-level sky terraces and the Sky Forest); Bank of America Tower SS6 = 2 (green roof plus highly reflective paving); Shanghai Tower SS2 = 3 (dense mixed-use Lujiazui setting with direct pedestrian links to the metro and adjacent towers); Bloomberg London SS6 = 0 (no project-specific source reviewed documents a green roof, high-SRI paving or any other site heat-mitigation strategy). Per-item evidence summaries, source identifiers and scoring rationales are reported in Supplementary Table S2. Two patterns emerge. First, the tropical case (CapitaGreen, Af) records the highest documented score on open space while also meeting the highest thresholds on urban connectivity and alternative transportation, so it does not display the connectivity-versus-ecology trade-off that a straightforward climate account would predict. Second, the cross-case spread cannot be attributed to climate and may also reflect whether project-specific ecological evidence could be verified—most clearly for Bloomberg London, where neither a qualifying heat-mitigation strategy (SS6 = 0) nor a designed green/open-space system (SS4 = 1) was documented. Possible interpretations and alternative explanations are discussed in Section 4.

To facilitate comparison across the six SS–LT site-performance criteria, the completed assessment scores are visualized as radar profiles in Figure 3. The figure highlights the similarities and differences among the five case-study buildings more clearly than the numerical matrix alone.

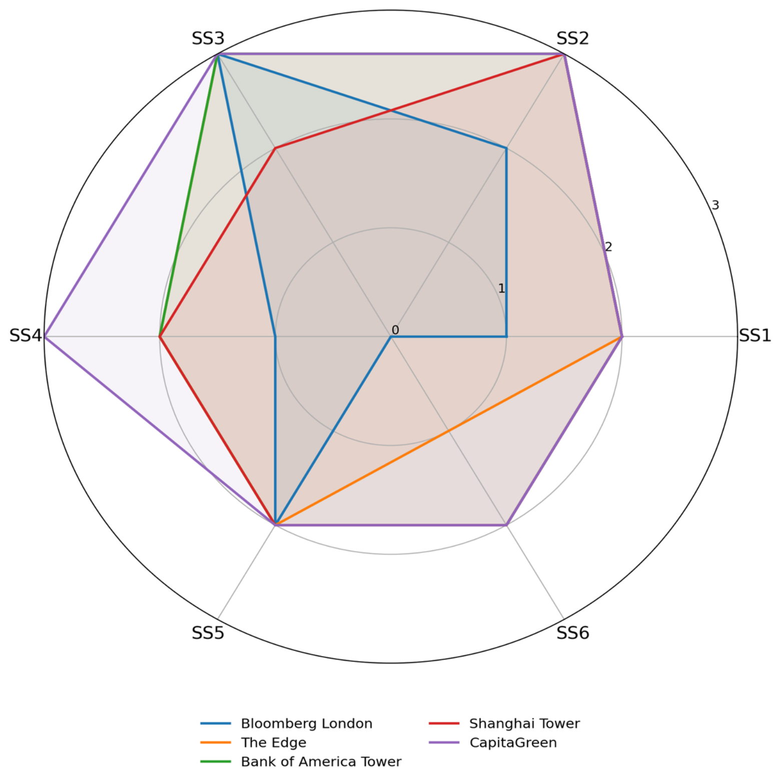

Figure 3. Radar profiles of the five buildings across the six SS–LT criteria (SS1–SS6). CapitaGreen records the highest or joint-highest documented score on all six criteria, while Bloomberg London records the lowest scores for open space (SS4 = 1) and heat-mitigation strategies (SS6 = 0). The radial scale ranges from 0 to 3, and the shaded polygons represent the five case-study buildings as identified in the legend.

As illustrated in Figure 3, the greatest variation occurs in the ecological criteria SS4 and SS6, whereas alternative transportation (SS3) and rainwater management (SS5) remain comparatively uniform across all five cases.

3.2. Smart Building Technology Matrix—Completed Scores (RQ2)

Following the evaluation of combined SS–LT site performance, the second stage of the framework assessed the documented implementation level of smart building technologies. Only the two indicators for which project-specific documentary sources could be verified—ST1 (Building Management Systems) and ST2 (environmental sensors)—were scored (Table 9); these constitute the basis for calculating the Technology Enablement Factor (TEF), which is reported alongside the weighted site-performance index. Per-cell sources and evidence limitations are reported in Supplementary Tables S2 and S5.

Table 9. Completed smart-technology scores (0–3) for the two indicators supported by project-specific documentary evidence. Per-item evidence, source identifiers and scoring rationales are reported in Supplementary Tables S2 and S5. ST3–ST5 were not scored (Section 2.4) and are omitted from this table.

Code	Indicator	Bloom.	Edge	BoA	Shanghai	Cap.
ST1	Building management systems	2	3	2	2	2
ST2	Environmental sensors	2	3	3	2	2

The Edge is the only case for which both a fully integrated building management platform and a building-wide environmental-sensing network are documented in project-specific sources, and it is therefore the only case scoring 3 on both indicators. Bank of America Tower attains the maximum score on environmental sensors—continuous CO_2, CO, VOC and particulate monitoring is documented alongside occupancy and daylight sensors—but is scored 2 on building management because no single building-wide digital platform could be verified. Bloomberg London, Shanghai Tower and CapitaGreen each score 2 on both indicators, and in every case the constraint is the same: multi-system automation is documented—integrated ceiling, HVAC and responsive-airflow systems at Bloomberg London, a facility network covering automation, energy management and metering at Shanghai Tower, and HVAC zoning with sensor-controlled lighting at CapitaGreen—without an explicit account of a project-wide integrated platform or of comprehensive multi-parameter sensing. These scores form the basis for calculating the Technology Enablement Factor (TEF). They measure documented implementation, not actual implementation; the distinction is discussed in Section 4.6.

3.3. Weighted Indices: SSPI and TEF (RQ2)

The completed Site-Performance Matrix and Smart Technology Matrix were subsequently combined using Equations (1) and (2) to calculate the SS–LT Site-Performance Index (SSPI) and the Technology Enablement Factor (TEF) computed over ST1–ST2. The two measures are reported side by side rather than merged into a single composite score. Table 10 summarizes the resulting weighted performance scores.

Table 10. Weighted site-performance indices (LEED-informed baseline weights) and the descriptive Technology Enablement Factor. The first, second and last positions are unchanged under the alternative weighting schemes tested; The Edge and Shanghai Tower are tied under the Equal and Ecology-sensitive schemes (Section 3.4, Table 11).

Building	SSPI	TEF	SSPI Rank
CapitaGreen	2.65	0.67	1
Bank of America Tower	2.59	0.83	2
The Edge	2.53	1.00	3
Shanghai Tower	2.29	0.67	4
Bloomberg London	2.00	0.67	5

TEF is reported beside SSPI rather than folded into it, so the site-performance ordering is determined only by documented SS–LT evidence (Figure 4). The Edge combines the highest TEF (1.00) with a mid-range SSPI, and the two measures therefore produce different orderings. The two leading cases are separated by only 0.06 SSPI points (CapitaGreen 2.65; Bank of America Tower 2.59), which should not be interpreted as a robust performance difference. TEF values span 0.67–1.00, while SSPI values span 2.00–2.65.

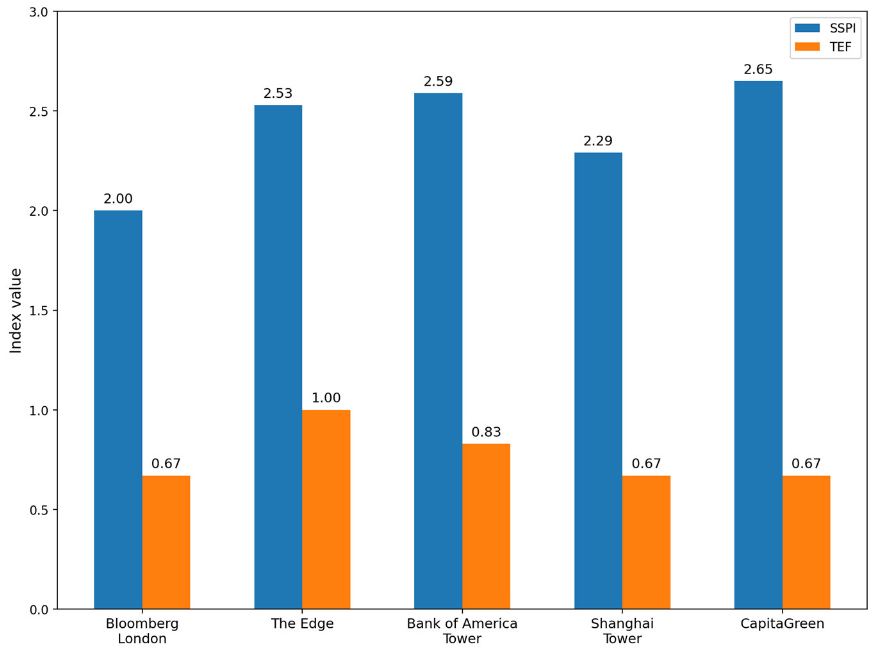

Figure 4. SS–LT Site-Performance Index (SSPI; 0–3) and descriptive Technology Enablement Factor (TEF; 0–1) by building. SSPI calculations use the exact normalized baseline weights; TEF uses the two retained indicators, ST1 and ST2. SSPI ranges from 2.00 to 2.65 and TEF from 0.67 to 1.00. The different case orderings show that documented smart-operational capability and documented SS–LT site performance are separate constructs in this workflow.

The aggregate SSPI values differ by 0.65 across the sample, a wider spread than the retained technology indicators produce, and the two measures do not order the cases in the same way.

3.4. Weighting Sensitivity and Ranking Concordance (RQ3)

The baseline SSPI values range from 2.00 to 2.65, with variation occurring mainly at criterion level. CapitaGreen reaches the highest documented level on urban connectivity, alternative transportation, and open space, while Bank of America Tower matches it on the two highest-weighted criteria. The exact baseline assigns 58.82% of total weight to SS2 and SS3; Bloomberg London's last position reflects its SS4 = 1, SS6 = 0, and SS2 = 2 documentary scores rather than a measured environmental-performance deficit.

To evaluate how sensitive the comparative ranking is to the adopted weighting structure, the SSPI was recalculated under the three weighting schemes defined in Table 7 (LEED-informed baseline, Equal, Ecology-sensitive). Table 11 summarizes the resulting rankings.

Table 11. Full building ranking under the three weighting schemes defined in Table 7. Values recalculated using the Table 8 criterion scores and the Ecology-sensitive weights specified by the authors (SS1 10%, SS2 15%, SS3 15%, SS4 20%, SS5 25%, SS6 15%).

Building	LEED-Informed Baseline	Equal Weights	Ecology-Sensitive
CapitaGreen	2.65 (Rank 1)	2.50 (Rank 1)	2.50 (Rank 1)
Bank of America Tower	2.59 (Rank 2)	2.33 (Rank 2)	2.30 (Rank 2)
The Edge	2.53 (Rank 3)	2.17 (Rank 3, tie)	2.15 (Rank 3, tie)
Shanghai Tower	2.29 (Rank 4)	2.17 (Rank 3, tie)	2.15 (Rank 3, tie)
Bloomberg London	2.00 (Rank 5)	1.50 (Rank 5)	1.55 (Rank 5)

The ranking was broadly stable but not invariant across the three weighting schemes. CapitaGreen remained first, Bank of America Tower second, and Bloomberg London last. Under the LEED-informed baseline, The Edge ranked third and Shanghai Tower fourth; under the Equal and Ecology-sensitive schemes, the two cases tied at 2.17 and 2.15, respectively. Bloomberg London ranged from 1.50 to 2.00, a 0.50-point spread, showing that weights affect score magnitude even where rank is unchanged. CapitaGreen remains first because it is not outscored by another case on any criterion in this specific matrix; this dominance property should not be generalized beyond the sample.

3.5. Multi-Criteria Ranking: TOPSIS Results

As a ranking-concordance check, the TOPSIS multi-criteria decision-making method was applied using the same LEED-informed baseline weighting structure and the same underlying scores as the SSPI. Comparing TOPSIS with the proposed SSPI provides a check on the arithmetic sensitivity of the ranking rather than an independent corroboration, since both methods draw on identical inputs. The resulting relative closeness coefficients (Ci*) are presented in Table 12.

Table 12. TOPSIS relative closeness coefficients (Ci*) and ranking (LEED-informed baseline weights).

Rank	Building	Ci* (Closeness)
1	CapitaGreen	1.000
2	Bank of America Tower	0.864
3	The Edge	0.784
4	Shanghai Tower	0.574
5	Bloomberg London	0.405

The matching order between TOPSIS and SSPI indicates that the ranking is not an artefact specific to the arithmetic form of the weighted-sum index: when the same data and weights are retained, an alternative multi-criteria method reproduces the same ordering. The result requires one qualification. Because CapitaGreen scores at least as highly as every other case on all six criteria, it coincides exactly with the positive-ideal solution, and its closeness coefficient of 1.000 follows by construction rather than from a measured degree of separation. The concordance is therefore a check on internal consistency under a dominance structure, not an independent validation of the framework.

4. Discussion

The principal finding is that the five cases exhibit different criterion-level SS–LT profiles despite relatively similar aggregate scores. These differences are interpreted in relation to climatic context, while recognizing that climate cannot be separated from urban morphology, infrastructure, building scale, certification background, and documentation availability in the present design.

4.1. Main Cross-Case Patterns

Across the five cases, criterion-level scores were not uniform, but the variation does not align cleanly with climate zone. CapitaGreen (Af) records the highest documented open-space score and also meets the highest thresholds on urban connectivity and alternative transportation; Bank of America Tower (Cfa) matches it on both connectivity criteria and on heat mitigation. The clearest differentiation in the sample is instead between cases for which project-specific ecological evidence could be verified and those for which it could not: Bloomberg London scores 1 on open space and 0 on heat mitigation, and The Edge scores 1 on heat mitigation, in each case because no qualifying project-specific source was identified rather than because a lower level of provision was established. This observation is consistent with Greer et al.'s [10] finding that LEED points are not always strongly linked to climatic outcomes, and with Zarghami and Ahmad's [9] call to re-examine how credit structures reflect regional priorities—though, with five cases that also differ in scale, density, and infrastructure, the present data cannot attribute the pattern to climate alone (see Section 4.5).

A practical implication worth testing in future, larger-sample research is that project teams might benefit from letting climatic and site context inform SS/LT strategy priorities at project inception, rather than targeting the highest-scoring credits uniformly; the present exploratory data are suggestive of this but do not establish it.

4.2. Interpretation in Relation to Previous Studies

The tropical case (CapitaGreen) illustrates one plausible interpretation of how climatic context may be associated with the documented emphasis placed on ecological interventions: it scored highest among the five cases on open space, and its heat-mitigation provision is documented through two complementary strategies, extensive vertical greenery and multi-level sky terraces. Wong et al. [36] reported that vertical greenery can lower surface temperature in tropical contexts, a pattern broadly consistent with CapitaGreen's documented SS6 = 2 strategies. Rainwater management, by contrast, was recorded at level 2 in all five cases, because retention and reuse were documented everywhere while water-specific sensor monitoring was verified nowhere; this criterion therefore does not differentiate the sample and cannot support a climate-related reading. The lower heat-mitigation scores of Bloomberg London and The Edge are consistent with, but do not demonstrate, a difference in documented strategy emphasis across the selected contexts. Singapore's substantially higher rainfall and temperature relative to London or Amsterdam (Table 3) offer a plausible physical rationale for this pattern, though the present single-case tropical comparison cannot rule out other explanations tied to CapitaGreen's specific site, scale, or certification documentation.

This pattern is broadly aligned with the direction LEED v5 has taken in strengthening its climate-resilience category [45]. Whether climate-calibrated benchmarks referenced to regional conditions would improve on standard North American or European reference cases is a testable question for future, larger-sample research rather than a conclusion this exploratory five-case study can support.

4.3. Influence of Weighting Assumptions

In this five-case dataset the leading, second and last positions proved stable across all three weighting schemes, while The Edge and Shanghai Tower tied under the equal and ecology-sensitive schemes and the index values themselves shifted substantially (Table 11). The stability of the extremes arises from a specific feature of the present matrix: CapitaGreen scores at least as highly as every other case on all six criteria, so no redistribution of weight among those criteria can displace it. The stability should therefore be attributed to the dominance structure of this particular sample rather than to robustness of the framework, and it does not contradict Ismaeel's [19] critique of the regional sensitivity of some LEED credit categories. The LEED-informed baseline assigns 58.82% of the total weight to connectivity and transportation, which structurally privileges these criteria within the present model. Whether this emphasis is appropriate across different regional contexts requires empirical investigation. That this choice left the leading and trailing positions unchanged does not make it neutral: it altered the middle-order differentiation, changed the reported index values by up to 0.50 on a 0–3 scale, and in a sample without a dominant case would be expected to affect the ordering as well. Weighting choice therefore remains a normative decision with real consequences for comparative results, not a neutral technical detail. CR-SSAF's inclusion of three weighting schemes makes this sensitivity visible rather than hidden inside a single aggregate score.

For certification bodies, one implication worth further investigation is that no single weighting scheme may be optimal for universal use. Future research could examine context-sensitive weighting approaches developed through larger-sample empirical testing and stakeholder consultation, or modular weighting interfaces that make user-defined priorities explicit. These are research directions, not recommendations supported by this five-case sample.

4.4. Methodological Contribution of the Scoring Workflow

Documented TEF values fall within a relatively narrow band across the five cases (0.67–1.00), and the shape of that distribution is itself the principal observation on this dimension: only one case (The Edge) is documented at the highest level on both retained indicators, one further case (Bank of America Tower) reaches that level on environmental sensors alone, and the remaining three sit uniformly at the intermediate level. In each of those three cases the constraint was identical: multi-system automation is documented, but no project-wide integrated platform or comprehensive multi-parameter sensor network is described. The pattern should be read as a property of the documentary record rather than of the buildings themselves. Equally informative is what could not be scored at all: the three indicators originally proposed—smart water monitoring, smart mobility integration and data-driven site management—were withdrawn from the index because no project-specific source reported them for any of the five cases, despite all five being unusually well-documented buildings. This is consistent with the observation of Bibri and Huang [14] and Oulefki et al. [13] that IoT and digital-twin capabilities are reported predominantly at the level of energy and HVAC systems, and it extends that observation by indicating that site-level smart functions remain largely unreported in public project documentation. The main methodological contribution, however, is not this pattern but the workflow that produced it: a documentation-based scoring procedure in which every reported score is tied to an explicit rubric threshold and a cited project-specific source (Supplementary Tables S2 and S5), and in which indicators lacking such a source are withdrawn rather than estimated.

Beyond the case-specific observations, the study makes a bounded procedural contribution. It shows how aggregate certification labels can be unpacked into source-linked criterion profiles and how those profiles change under alternative normative weights. Climate descriptors are used only to organize hypotheses for future research; the present data do not show that climate causes, moderates, rewards, or increases the effectiveness of any strategy. Similarly, TEF records documentary evidence of management and sensor systems rather than measured site-level benefit. CR-SSAF's contribution is therefore the visibility it gives to evidence, thresholds, and assumptions, not proof of climate effects, framework validity, or transferability.

4.5. Alternative Explanations and Confounding Factors

Because the five cases differ not only in climate but also in urban morphology, building scale, transit infrastructure, certification system, and the completeness of publicly available documentation, any cross-case difference observed in Section 3 could plausibly reflect one or more of these factors rather than climate alone. Table 13 summarizes the strategy emphasis actually observed in each case grouped by climatic context, as a descriptive record rather than a validated design-priority framework. In the present matrix the tropical CapitaGreen site records both the highest documented ecological score on open space and the highest thresholds on the connectivity-related criteria, so the sample does not display the trade-off between connectivity and ecological provision that a climate-driven account would predict. Singapore's regulatory context provides an important alternative explanation: the Urban Redevelopment Authority's Landscape Replacement Area requirements for Strategic Areas require displaced ground-level greenery to be replaced through accessible ground-level, rooftop, or sky-terrace landscaping [46]. These requirements offer at least as plausible an explanation for CapitaGreen's documented open-space result as climate itself, and were not independently measured in this study.

Table 13. Observed case-level strategy emphasis by climatic context (descriptive summary, not a validated design-priority framework).

Climatic Context	Observed Strategy Emphasis
Temperate (Cfb)—London, Amsterdam	Alternative transportation and, for Amsterdam, urban connectivity (SS3 = 3; SS2 = 3 for The Edge, 2 for Bloomberg London). Documented ecological provision is the weakest in the sample (Bloomberg London SS4 = 1, SS6 = 0; The Edge SS6 = 1). Technology documentation is the fullest in the sample for The Edge (ST1–ST2 = 3) and intermediate for Bloomberg London.
Humid subtropical (Cfa)—New York, Shanghai	Urban connectivity (SS2 = 3), rainwater retention and reuse (SS5 = 2), and two documented heat-mitigation strategies each (SS6 = 2). Alternative transportation differentiates the pair (New York 3, Shanghai 2). Technology documentation is intermediate to high (TEF 0.67–0.83).
Tropical (Af)—Singapore	Highest documented open space in the sample (SS4 = 3) together with the highest thresholds on urban connectivity and alternative transportation (SS2–SS3 = 3) and two documented heat-mitigation strategies (SS6 = 2). Technology documentation is intermediate (TEF 0.67).

4.6. Limitations

This study is exploratory, and its findings should be read within the following limitations. (i) The sample is limited to five buildings (n = 5), so only analytical, not statistical, generalization is intended [27]. (ii) Only one case represents the Af (tropical) climate zone, so patterns attributed to that zone rest on a single building. (iii) The cases are not independent of one another in a statistical sense (shared office typology, shared certification-era construction practices), which further limits generalization. (iv) Climate and urban context are not separable in this design: differences in urban morphology, building scale, and infrastructure covary with climate zone across the five cases and cannot be disentangled with the available data (Section 4.5). (v) The buildings differ substantially in scale and height, which may independently affect several SS–LT criteria. (vi) The five buildings were documented under different certification systems (LEED, BREEAM, BCA Green Mark) with different reporting conventions and levels of public documentation detail, a potential source of evidence bias (Section 2.1). (vii) Scoring relies on publicly available project documentation; absence of documented evidence for a strategy does not necessarily mean the strategy is absent on site, only that it was not found in the available public record. (viii) No measured operational environmental-performance data (e.g., metered stormwater retention volumes, measured surface temperatures) were available; scores reflect documented design intentions and reported features rather than verified operational outcomes. (ix) No occupant or operational-use data were analyzed. (x) The three weighting schemes (LEED-informed baseline, equal, ecology-sensitive) are normative choices, not empirically derived or validated weights; the ecology-sensitive scheme in particular is a hypothetical sensitivity scenario (Section 2.5). (xi) Although SS2, SS3, ST1, and ST2 now use component-count and scope rules, the reviewed sources do not consistently report standardized distances, areas, capacities, or network-coverage percentages; the revised thresholds improve reproducibility but do not convert documentary evidence into continuous performance measures. (xii) The operational rubric (Table 5) has not been tested for construct, criterion, or predictive validity; inter-rater agreement (Section 2.7) demonstrates only that two researchers could apply the rubric consistently, not that the rubric measures what it is intended to measure. (xiii) Because the design does not isolate climate from these covarying factors, the results cannot be interpreted as evidence of a climate effect on combined SS–LT site performance, only as patterns consistent with, among other possible explanations, a climate-related interpretation. (xiv) The effect of occupant behaviour was not analyzed directly [4]. (xv) Three of the five smart-technology indicators originally specified (ST3–ST5) were withdrawn from the index because no project-specific documentary source reporting sensor-driven water monitoring, smart mobility integration or data-driven landscape management could be identified for any of the five cases; the Technology Enablement Factor therefore rests on two indicators only, and its values reflect the availability of documentation as much as technological capability. (xvi) The project-specific sources available for the retained technology indicators are architect, engineer, developer and certification-body project records rather than peer-reviewed studies or full certification scorecards, and none of the five cases is documented by a peer-reviewed study or a full certification scorecard on this dimension. (xvii) The climatic description is limited to Köppen class, mean temperature, and annual rainfall and therefore does not capture humidity, solar exposure, wind, degree-day demand, or climatic extremes.

Returning to the three research questions stated in Section 1.1:

RQ1 (What criterion-level site-performance patterns are observed across the five cases?) is addressed by Sections 3.1 and 4.1: alternative transportation and rainwater management were documented at a similar level across all five cases, whereas open space (SS4) and heat mitigation (SS6) showed the widest cross-case variation, each spanning a two-point range; the tropical case recorded the highest documented score on open space while also meeting the highest connectivity and transportation thresholds. The observed variation cannot be attributed to climate zone and may also reflect differences in project-specific ecological documentation and other contextual factors (Sections 4.5 and 4.6).

RQ2 (How are documented smart building technologies represented within the workflow?) is addressed by Sections 3.2, 3.3 and 4.4: of the five technology indicators initially specified, only two (ST1, ST2) could be supported by project-specific documentary sources across the cases, and the resulting TEF values ranged from 0.67 to 1.00, with the fullest documentation for The Edge and with three of the five cases sitting at the same intermediate level.

RQ3 (How sensitive are comparative rankings to alternative criterion weights?) is addressed by Table 11 and Section 4.3: the first, second and last positions were unchanged across all three weighting schemes; The Edge ranked third and Shanghai Tower fourth under the LEED-informed baseline, while the two cases tied under the Equal and Ecology-sensitive schemes, and the index values themselves shifted by up to 0.50. The leading and trailing positions are stable in this dataset because one case scores at least as highly as every other on all six criteria; this stability is therefore a property of the present sample rather than evidence that the framework is insensitive to weighting, and the weighting choice remains a consequential normative decision.

Future research building on this exploratory workflow should prioritize larger and more diverse building samples that would permit statistical (rather than only analytical) generalization, additional building typologies, and a wider range of Köppen climate zones, particularly additional tropical (Af) cases. Rater-level scores are retained and reported in Supplementary Table S3, and weighted-kappa results in Supplementary Table S4; the more informative extension for future applications would be independent evidence retrieval by each rater, so that agreement reflects the reproducibility of the evidence base and not only of the rubric. Incorporating measured operational performance data and occupant-related indicators would help test whether the documented design patterns observed here correspond to measured environmental outcomes. Future applications may also extend the workflow to other certification systems, such as BREEAM, DGNB, Green Star, and CASBEE, and could apply regression or multilevel methods once a sufficiently large and climate-diverse sample is available to test climate's association with SS–LT performance while controlling for the confounding factors identified in Section 4.5.

5. Conclusions

This study demonstrates CR-SSAF as an exploratory documentation-based workflow for a combined SS–LT construct across five green-certified smart office buildings in three Köppen climate zones. Alternative transportation and rainwater management were documented at similar levels across the cases, while open space and exterior heat mitigation showed the widest variation. The Af case recorded the highest SSPI in this sample, but the cases also differ in urban form, scale, infrastructure, regulation, certification background, and documentation. The observed differences therefore generate hypotheses; they do not establish a climate effect.

The methodological contribution is the explicit separation of source-linked ordinal scoring, normative weighting, smart-operational documentation, and contextual climate interpretation. Sensitivity analysis shows that weighting choices alter score magnitudes and the middle ranks, while TEF and SSPI yield different case orderings. Table 13 is consequently a descriptive, hypothesis-generating summary rather than a climate-based design-priority model.

The exploratory nature of this study points to several directions for future research, including statistical testing of the observed patterns using larger and more diverse building samples, independent evidence retrieval by each rater, so that reliability statistics capture the reproducibility of the evidence base and not only of the rubric, empirical testing of climate's association with SS–LT performance while controlling for urban morphology, scale, and infrastructure, comparison across multiple green building certification systems, and validation using measured operational performance data. Extending the workflow to additional Köppen climate zones and building typologies would further test its applicability.

Testing the observed cross-case patterns and establishing applicability beyond this sample require larger and climate-balanced samples, measured environmental outcomes, standardized project documentation, and fully independent evidence retrieval and scoring.

Supplementary Materials: The following supporting information can be downloaded at: https://www.mdpi.com/article/10.3390/buildings16163247/s1. Table S1: CR-SSAF scoring questions, ordinal rubric and confidence definitions; Table S2: Case-by-criterion evidence matrix and shared evidence-based scoring rationales; Table S3: Rater-level scores, confidence assessments and agreement status; Table S4: Inter-rater reliability results and agreement matrices; Table S5: Official and institutional source register. The two rater score workbooks and the inter-rater reliability calculation workbook are provided as Supplementary Data.

Author Contributions: Conceptualization, M.S.A. and E.Y.; methodology, M.S.A. and E.Y.; formal analysis, M.S.A.; investigation, M.S.A. and E.Y.; data curation, M.S.A. and E.Y.; writing—original draft preparation, M.S.A.; writing—review and editing, E.Y.; visualization, M.S.A.; supervision, E.Y. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Data Availability Statement: The final scores, calculation procedures, and documentary evidence are reported in the article and in Supplementary Materials Tables S1–S5. Rater-level scores, per-item confidence ratings, agreement matrices, and the full source register are provided in Supplementary Tables S3– S5 and are available for secondary analysis. The two rater workbooks and the inter-rater reliability calculation workbook are provided as Supplementary Data. All reported scores are supported by cited project-specific sources listed in Supplementary Table S5; no score is reported provisionally, and the three smart-technology indicators for which no such source could be identified (ST3–ST5) were withdrawn from the analysis rather than reported provisionally. No new experimental datasets were generated; the analysis is based on publicly available certification documentation and official long-term meteorological records cited in the References.

Acknowledgments: During the preparation and revision of this manuscript, the authors used ChatGPT (OpenAI, GPT-5.6 Sol, web version; accessed in August 2026) for language editing, formatting assistance, consistency checking, and the preparation of draft graphical layouts. All AI-assisted output was critically reviewed and edited by the authors, who take full responsibility for the content of this publication.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

Abbreviation	Definition
CR-SSAF	Climate-Referenced SS–LT Site-Performance Assessment Framework
SS	Sustainable Sites
LT	Location and Transportation
SSPI	SS–LT Site-Performance Index
TEF	Technology Enablement Factor
LEED	Leadership in Energy and Environmental Design
TOPSIS	Technique for Order of Preference by Similarity to Ideal Solution
BMS	Building Management System
HVAC	Heating, Ventilation, and Air Conditioning
AI	Artificial Intelligence
IoT	Internet of Things
BREEAM	Building Research Establishment Environmental Assessment Method
SRI	Solar Reflectance Index
LID	Low-Impact Development
PV	Photovoltaic

References

1. Pérez-Lombard, L.; Ortiz, J.; Pout, C. A review on buildings energy consumption information. *Energy Build.* **2008**, *40*, 394–398. [CrossRef]
2. Kibert, C.J. *Sustainable Construction: Green Building Design and Delivery*, 4th ed.; Wiley: Hoboken, NJ, USA, 2016.
3. Ma, Z.; Cooper, P.; Daly, D.; Ledo, L. Existing building retrofits: Methodology and state-of-the-art. *Energy Build.* **2012**, *55*, 889–902. [CrossRef]
4. Kim, D.; Yoon, Y.; Lee, J.; Mago, P.J.; Lee, K.; Cho, H. Design and Implementation of Smart Buildings: A Review of Current Research Trend. *Energies* **2022**, *15*, 4278. [CrossRef]
5. Al Dakheel, J.; Del Pero, C.; Aste, N.; Leonforte, F. Smart Buildings Features and Key Performance Indicators: A Review. *Sustain. Cities Soc.* **2020**, *61*, 102328. [CrossRef]
6. Cole, R.J.; Sterner, E. Reconciling theory and practice of sustainable building: The issue of building performance. *Build. Res. Inf.* **2000**, *28*, 460–467.
7. U.S. Green Building Council. *LEED V4 for Building Design and Construction*; USGBC: Washington, DC, USA, 2013.
8. Ding, G.K.C. Sustainable construction—The role of environmental assessment tools. *J. Environ. Manag.* **2008**, *86*, 451–464. [CrossRef] [PubMed]

9. Zarghami, S.A.; Ahmad, T. Empirical evaluation of the LEED green building rating system: Exploring limitations through configurational analysis. *Build. Res. Inf.* **2026**, *54*, 257–272. [CrossRef]
10. Greer, F.; Chittick, J.; Jackson, E.; Mack, J.; Shortlidge, M.; Grubert, E. Energy and water efficiency in LEED: How well are LEED points linked to climate outcomes? *Energy Build.* **2019**, *195*, 161–167. [CrossRef]
11. Reinhart, C.F.; Davila, C.C. Urban building energy modeling: A review of a nascent field. *Build. Environ.* **2016**, *97*, 196–202. [CrossRef]
12. Tahmasebinia, F.; Lin, L.; Wu, S.; Kang, Y.; Sepasgozar, S. Exploring the benefits and limitations of digital twin technology in building energy. *Appl. Sci.* **2023**, *13*, 8814. [CrossRef]
13. Oulefki, A.; Kheddar, H.; Amira, A.; Kurugollu, F.; Himeur, Y.; Bounceur, A. Innovative AI strategies for enhancing smart building operations through digital twins: A survey. *Energy Build.* **2025**, *335*, 115567. [CrossRef]
14. Bibri, S.E.; Huang, J. AI and AI-powered digital twins for smart, green, and zero-energy buildings: A systematic review of leading-edge solutions for advancing environmental sustainability goals. *Environ. Sci. Ecotechnol.* **2025**, *28*, 100628. [CrossRef] [PubMed]
15. Cespedes-Cubides, A.S.; Jradi, M. A review of building digital twins to improve energy efficiency in the building operational stage. *Energy Inform.* **2024**, *7*, 11. [CrossRef]
16. Hafez, F.S.; Sa'di, B.; Safa-Gamal, M.; Taufiq-Yap, Y.H.; Alrifaey, M.; Seyedmahmoudian, M.; Stojcevski, A.; Horan, B.; Mekhilef, S. Energy efficiency in sustainable buildings: A systematic review. *Energy Strategy Rev.* **2023**, *45*, 101013. [CrossRef]
17. Hwang, C.L.; Yoon, K. *Multiple Attribute Decision Making: Methods and Applications*; Springer: Berlin/Heidelberg, Germany, 1981.
18. Yu, W.; Haghighat, F.; Fung, B.C.M. A decision-making model for building energy management considering sustainability. *Build. Environ.* **2011**, *46*, 1089–1096.
19. Ismaeel, W.S.E. The dynamics of sustainable material selection for green-certified projects. *Buildings* **2023**, *13*, 2077. [CrossRef]
20. Panchalingam, R.; Chan, K.C. A state-of-the-art review on artificial intelligence for Smart Buildings. *Intell. Build. Int.* **2021**, *13*, 203–226. [CrossRef]
21. BRE Group. *Bloomberg London—BREEAM Case Study*; Building Research Establishment: Watford, UK, 2017. Available online: https://bregroup.com (accessed on 1 June 2025).
22. Bloomberg, L.P. *Bloomberg's New European Headquarters Rated World's Most Sustainable Office Building*; Bloomberg, L.P.: New York, NY, USA, 2017. Available online: https://www.bloomberg.com/company/press/bloomberg-most-sustainable-office-building/ (accessed on 1 June 2025).
23. COOKFOX Architects. *One Bryant Park—Project Documentation*; COOKFOX Architects: New York, NY, USA, 2021. Available online: https://cookfox.com/projects/one-bryant-park/ (accessed on 1 June 2025).
24. Cosentini Associates (Tetra Tech). *Shanghai Tower: Achieving LEED Platinum in a Supertall Building—Project Record*; Tetra Tech: Pasadena, CA, USA, 2023. Available online: https://www.tetratech.com (accessed on 1 June 2025).
25. CapitaLand. *CapitaGreen Factsheet*; CapitaLand Ltd.: Singapore, 2016. Available online: https://www.capitaland.com (accessed on 1 June 2025).
26. Centre for Digital Built Britain. *The Edge, Amsterdam—Showcasing an Exemplary IoT Building*; University of Cambridge: Cambridge, UK, 2018.
27. Yin, R.K. *Case Study Research and Applications: Design and Methods*, 6th ed.; SAGE: Thousand Oaks, CA, USA, 2018.
28. Holt, D. Bloomberg European Headquarters, London [Photograph]; Wikimedia Commons; Licensed Under CC BY 2.0. Available online: https://commons.wikimedia.org/wiki/File:Bloomberg_European_Headquarters,_London.jpg (accessed on 3 August 2026).
29. Eden, J. One Bryant Park (8156006545) [Photograph]; Wikimedia Commons; Licensed Under CC BY 2.0. Available online: https://commons.wikimedia.org/wiki/File:One_Bryant_Park_(8156006545).jpg (accessed on 3 August 2026).
30. Xiquinhosilva. Shanghai Tower (32910112532) [Photograph]; Wikimedia Commons; Licensed Under CC BY 2.0. Available online: https://commons.wikimedia.org/wiki/File:Shanghai_Tower_(32910112532).jpg (accessed on 3 August 2026).
31. Jongeneel, H. The Edge—Panoramio [Photograph]; Wikimedia Commons; Licensed Under CC BY 3.0. Available online: https://commons.wikimedia.org/wiki/File:The_Edge_-_panoramio.jpg (accessed on 3 August 2026).
32. DvTor8303. CapitaGreen Tower 20250904 [Photograph]; Wikimedia Commons; Released Under CC0 1.0 (Public Domain Dedication). Available online: https://commons.wikimedia.org/wiki/File:CapitaGreen_Tower_20250904.jpg (accessed on 3 August 2026).
33. Torcellini, P.; Pless, S.; Deru, M.; Crawley, D. *Zero Energy Buildings: A Critical Look at the Definition*; NREL: Golden, CO, USA, 2006.
34. U.S. Green Building Council. *World's Second Largest Building, Shanghai Tower, Achieves LEED Platinum*; USGBC: Washington, DC, USA, 2015.
35. BRE Group. *The Edge, Amsterdam—BREEAM Case Study*; Building Research Establishment: Watford, UK, 2018. Available online: https://bregroup.com/case-studies/the-edge-amsterdam (accessed on 1 June 2025).

36. Wong, N.H.; Tan, A.Y.K.; Tan, P.Y.; Wong, N.C. Energy simulation of vertical greenery systems. *Energy Build.* **2009**, *41*, 1401–1408. [CrossRef]
37. Beck, H.E.; Zimmermann, N.E.; McVicar, T.R.; Vergopolan, N.; Berg, A.; Wood, E.F. Present and future Köppen–Geiger climate classification maps at 1-km resolution. *Sci. Data* **2018**, *5*, 180214. [CrossRef] [PubMed]
38. Royal Netherlands Meteorological Institute (KNMI). *Climate Normals: Amsterdam/Schiphol (1991–2020)*; KNMI: De Bilt, The Netherlands, 2024.
39. NOAA National Centers for Environmental Information. *U.S. Climate Normals: New York Central Park (1991–2020)*; NOAA: Asheville, NC, USA, 2024.
40. China Meteorological Administration. *Climatological Normals: Shanghai*; CMA: Beijing, China, 2024.
41. Meteorological Service Singapore. *Climate of Singapore: Long-Term Temperature and Rainfall Records*; National Environment Agency: Singapore, 2024.
42. Met Office. *UK Climate Averages: London Area (1991–2020)*; UK Meteorological Office: Exeter, UK, 2024.
43. Landis, J.R.; Koch, G.G. The measurement of observer agreement for categorical data. *Biometrics* **1977**, *33*, 159–174. [CrossRef]
44. Krippendorff, K. *Content Analysis: An Introduction to Its Methodology*, 4th ed.; SAGE: Thousand Oaks, CA, USA, 2018.
45. U.S. Green Building Council. *LEED V5 for Building Design and Construction*; USGBC: Washington, DC, USA, 2025.
46. Urban Redevelopment Authority (URA). *Greenery: Landscaping for Urban Spaces and High-Rises (LUSH)—Landscape Replacement Area Requirements*; URA: Singapore, 2026. Available online: https://www.ura.gov.sg/guidelines/development-control/development-control-handbooks/non-residential/sr/greenery/ (accessed on 5 August 2026).