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Review

Examining Energy Efficiency Practices in Office Buildings through the Lens of LEED, BREEAM, and DGNB Certifications

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Abstract: Energy accounts for a significant share of carbon emissions, and buildings play a substantial role in this by contributing to both direct and indirect emissions throughout their lifecycle. Enhancing energy efficiency in buildings is a strategy to mitigate these impacts. The main goal of this review is to uncover solutions, trends, and examples of good practices in the field of office buildings. It presents effective cases and a SWOT analysis of LEED, BREEAM, and DGNB certifications, highlighting their contributions to energy efficiency in buildings on an international scale. The paper identifies and outlines similarities and differences between each methodology used to achieve energy efficiency in different buildings and contexts. The findings may allow new ways to improve access and obtain results regarding energy efficiency, thereby supporting building owners and companies in finding more effective solutions. The research highlights the necessity for continual enhancements in these systems, which should involve addressing economic factors, conducting post-occupancy evaluations, and considering lifecycle perspectives. The recommendations encompass standardizing practices, considering costs, conducting regular revisions, managing materials and resources, and incorporating occupancy measures.

Keywords: certification; LEED; BREEAM; DNGB; nZEB; rating systems; energy codes

Citation: Rebelatto, B.; Salvia, A.; Brandli, L.; Leal Filho, W. Examining Energy Efficiency Practices in Office Buildings through the Lens of LEED, BREEAM, and DGNB Certifications. *Sustainability* **2024**, *16*, 4345. https://doi.org/10.3390/su16114345

Academic Editor: Antonio Caggiano

Received: 19 March 2024
Revised: 8 May 2024
Accepted: 20 May 2024
Published: 21 May 2024

1. Introduction

Energy efficiency refers to the use of less energy to perform a specific task, minimizing energy waste, and can be related to systems or technologies that reduce energy consumption and lower energy costs [1]. It is emphasized by United Nations' Sustainable Development Goal 7 (SDG 7) which focuses on the universal availability of affordable, dependable, and environmentally sustainable energy access for all individuals [2]. According to du Can et al. [3], energy efficiency is a priority for achieving sustainable energy development, also considered by many policymakers and energy experts. In addition, their study shows how energy efficiency plays a direct role in lowering the financial burden associated with energy consumption for consumers. By doing so, it enhances the affordability of energy access and contributes to the advancement of countries in achieving SDG 7.

Energy-related carbon emissions were approximately 41.3 Gt in 2022, representing a total of 89% of the carbon emissions in the world [4]. The economic growth of countries is usually accompanied by rising energy demands. Since some of these demands are associated with energy use in buildings, it is important to take this into account. Consequently, transitioning toward a low-carbon energy system becomes crucial in order to reduce greenhouse gas (GHG) emissions and achieve the SDGs [5]. The IRENA report [6] emphasizes that lowering the primary energy intensity by improving energy efficiency, along with increasing the adoption of electrification by renewable energy, are excellent approaches to reduce emissions. Nam and Jin [5] agreed that to reduce carbon emissions, it is necessary to combine strong policy support with suitable regulatory framework and institutional arrangement. All these aspects are supported by SDG 13: take urgent action to combat climate change and its impacts [2].

In this scenario, the operational activities of buildings contribute to 30% of worldwide final energy usage and 26% of global energy-related emissions. Among these emissions, 8% stem from direct sources within buildings, while 18% arise indirectly from the production of electricity and heat utilized within these structures [4]. Electricity consumption in buildings operations represents approximately 55% of global electricity consumption, and 9% of the total 30% of global energy consumption is from non-residential buildings [7]. These numbers highlight the urgent call needed in the building sector to promote the construction of new energy-efficient buildings and the retrofitting of existing ones. After 2030, all newly constructed buildings must achieve zero energy; as for existing buildings, the rate of renovations will have to increase twofold, reaching two percent of the total building stock annually until 2030 [6].

Energy retrofits in existing buildings can potentially lower energy consumption by over 60%. Despite approximately 30% of the global building stock projected for 2030 yet to be constructed, nearly 75% of countries currently lack mandatory energy codes for new buildings [6]. To achieve net-zero emissions (nZEB) by 2050, severe adherence to mandatory energy-related building codes is crucial, with existing codes requiring enhancement. Such measures could result in a reduction of approximately 50% in the average energy intensity of new buildings between 2020 and 2030 [6], representing the efforts that can be achieved regarding Sustainable Development Goal 11 (SDG 11): make cities and human settlements inclusive, safe, resilient, and sustainable [2]. It is crucial to assess the contributions of renewable energy generation in achieving decarbonization goals, especially in nZEBs, using lifecycle assessment (LCA) frameworks and databases [8].

Hassan and El-Rayes' [9] analysis highlights the model's ability to identify the most cost-effective renewable energy measures for upgrading buildings while meeting all owner requirements and ensuring compliance with functional and constructability constraints. This supports building owners and decision-makers in integrating renewable energy into existing buildings. Lu et al. [10] emphasized the importance of government and stakeholder efforts in promoting renewable energy adoption for a sustainable energy future. They recommend implementing policies such as Building Energy Performance Certification (BEPC) schemes to accurately predict the annual energy demand and create a market where energy-efficient buildings are in demand. Chrysikopoulos et al. [11] noted the evolution of mechanisms and practices related to green certificates in response to changing energy markets and policy environments as the renewable energy sector expands.

In Europe, energy performance certificates were established in accordance with the Energy Performance Buildings Directive [12,13], aiming to contribute to the achievement of energy efficiency goals by providing pertinent information to stakeholders within the construction industry regarding buildings' energy efficiency [14]. In terms of office green certification, there is a notable quantitative advantage. Investors demonstrate a willingness to allocate 19 percent more value towards an office building that holds green certifications compared to a similar non-certified counterpart. This discovery strongly indicates that the advantages linked with green investments are substantial and are likely to outweigh the considerable expenses associated with green certification [15].

A sustainability approach in the construction sector offers numerous benefits, impacting environmental, economic, and social dimensions. Table 1 outlines some of these benefits. These advantages highlight the fact that a sustainability approach in the construction sector not only mitigates the negative impacts on the environment but also offers substantial economic and social benefits, contributing to more livable buildings.

Table 1. Some benefits of a sustainability approach in the construction sector.

Planetary Health Component	Benefit to the Construction Sector
Promotion of sustainable practices	By integrating sustainability concepts, the construction sector can engage in practices which may minimize the carbon footprint of building operations.
Energy efficiency	Buildings designed with sustainability in mind often incorporate energy-efficient systems, reducing energy consumption and greenhouse gas emissions.
Resources conservation	Sustainable construction encourages the use of renewable and less-resource-intensive materials, thus conserving natural resources.
Enhance resilience	Buildings constructed with sustainability principles in mind may be more resilient to environmental stressors, such as extreme weather events, excess heat or cold weather, and other patterns due to climate change.
Reduced waste production	Sustainability-oriented practices can often lead to cost savings, for example, through the reduced production of construction waste, reduced use of disposable materials, or a more efficient use of resources.
Resource conservation	Sustainable construction encourages the use of renewable and less-resource-intensive materials, thus conserving natural resources.
Increases in property value	Sustainable buildings can attract higher property values due to their modern features, efficiency, and lower operational costs.
Healthier living environment	Sustainable buildings often provide better indoor air quality, natural lighting, and thermal comfort, contributing to the wellbeing and productivity of occupants.

Source: authors.

For this study, the rating systems chosen were LEED, BREEAM, and DGNB. These certifications analyzed are not legally binding but are widely used in the construction industry to demonstrate a commitment to sustainability. LEED and BREEAM are pioneers and the most popular assessment tools cited in the literature [16–18]. Furthermore, BREEAM's inclusion of national annexes for different countries expands its relevance and suitability across various geographic regions [19]. DGBN is a well-recognized second-generation approach rooted in the principles of life cycle assessment [20].

Despite the fact that much research has been focusing on energy efficiency practices and the building sector [21–24], there is a research gap with respect to rating systems and their contributions and limitations. Against this background, the main goal of this review is to uncover solutions, trends, and examples of good practices in the field of office buildings. It presents effective cases and a SWOT analysis of LEED, BREEAM, and DGNB certifications, highlighting their contributions to energy efficiency in buildings on an international scale. It also identifies and outlines similarities and differences between each methodology used to achieve energy efficiency results in the different buildings where it is being developed. The contribution of this study emphasizes several critical areas for enhancing sustainability evaluation frameworks in construction. It addresses the necessity for continuous improvements in these systems. These may allow new ways to improve access and obtain results regarding energy efficiency, helping buildings owners/companies to find solutions that are capable of good results.

2. Theory Background

2.1. Energy Efficiency and Net-Zero-Energy Buildings (nZEBs)

Cao et al. [25] indicated that a significant portion of individuals spend most of their time indoors, which contributes significantly to the overall energy consumption of buildings. Furthermore, the entire lifecycle of a building is directly and indirectly responsible for 37% of the global CO_2 emissions related to energy, necessitating emissions restrictions throughout a building's lifecycle [26]. Zhong et al. [27] asserted that to address concerns about climate change, an ambitious improvement in building energy intensity, coupled with a transition to emission-free energy, is necessary.

According to the sixth report from the Intergovernmental Panel on Climate Change [28], buildings play a major role in the transition to a low-carbon and energy-efficient society. Zero-energy buildings (ZEBs) can be described as buildings that produce sufficient renewable energy to counterbalance their greenhouse gas emissions over their lifetime [29]. To achieve this qualification in a building, it is necessary to consider the design, materials, and systems (heating, cooling, lighting, and appliances) [30], not just during the design phase, but also throughout construction and operation. As indicated by [31], by adopting conservation and energy efficiency strategies, new buildings hold the capacity to cut the energy demand by half in comparison to conventional buildings.

Wetter [32] emphasized that one way to achieve energy efficiency in buildings is by using energy models as methods to create a virtual and real situation, allowing for the representation, reconfiguration, and addition of different components and topologies of buildings. Furthermore, the models used in the building's operational phase need to ensure maintenance levels, portability, and the ability to upgrade facilities for new technologies as buildings are adapted. However, existing buildings are being retrofitted at a very low rate [33], and different retrofit measures may have varying impacts on associated building subsystems due to various interactions. These impacts and interactions can make the process of selecting retrofit technologies even more complex [34].

2.2. Energy Efficiency and Certification Methods

Since the early 1990s, most developed countries have witnessed the gradual development of voluntary and mandatory environmental or energy certification schemes in the real estate sector to reduce carbon emissions from the construction industry [35]. Many regulations incorporate the thermal performance of the building envelope as a partial basis, often reflecting its influence on the building's energy efficiency through a labeling system. Furthermore, certain energy regulations utilize varying degrees of computational building performance simulation, commonly referred to as Building Energy Simulations (BESs), as part of the labeling process [36].

Figure 1 illustrates a comprehensive study on methods for evaluating energy efficiency based on global consumption and primary energy that was conducted by the Brazilian Center for Energy Efficiency in Buildings [37]. The authors analyzed 53 countries from Europe, Asia, South America, North America, Central America, Oceania, the Middle East, Asia, and Africa. Regarding efficiency classes, most standards (36 countries) use an alphabetical scale. In the remaining countries, the scale varies between numeric scales, stars, colors, or qualitative classes (platinum, gold, and silver). When it comes to the type of energy considered in the performance calculations, 31 countries use primary energy, and 22 use indicators of final energy consumption. Regarding the consumption indicator, 43 countries provide information on building energy consumption, with 35 using the indicator of energy consumption per unit of area per year (in kWh/m^2/year) and 10 analyzed standards having other specific evaluation criteria. The authors concluded that displaying the consumption level on the label makes labeling more accessible to consumers, as it shows the limits for each level and presents the obtained indicator. This allows consumers to assess how far the building ranks below or above the analyzed limits.

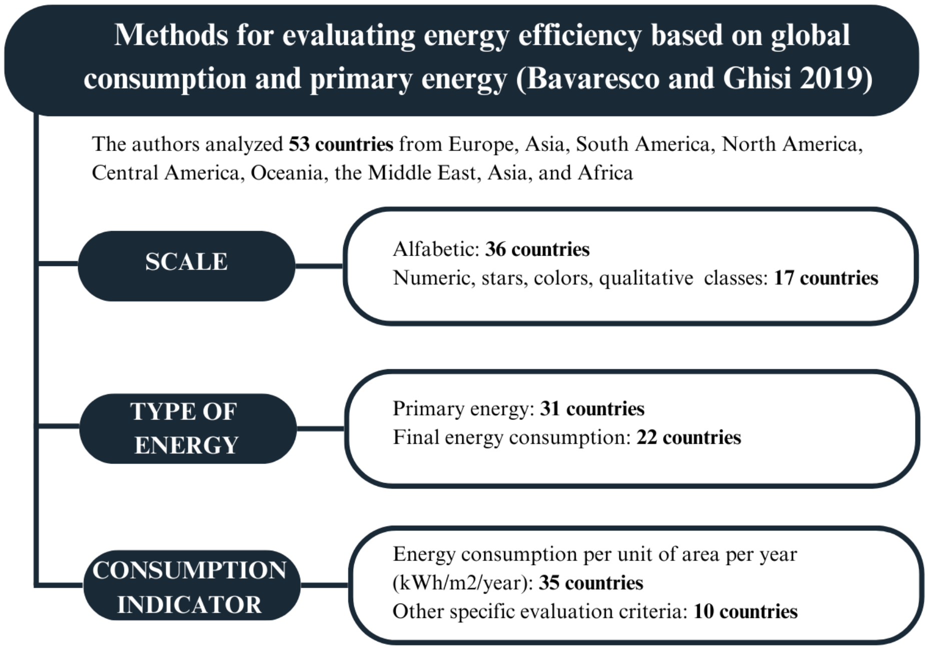

Figure 1. Method for evaluating energy efficiency, according to Bavaresco and Ghisi [37].

Currently, there are numerous publicly available Sustainable Certification Systems (SCS) utilized in the construction sector, each differing in its scope, criteria, assessment procedures, or models [38,39]. According to Mattoni et al. [40], BREEAM, from the United Kingdom—the pioneer among these systems—and LEED, from the United States, are the most recognized and widely adopted international systems. A bibliometric study conducted by Jiménez-Pulido [41] highlights that most existing SCSs are market-driven tools, backed by organizations like the World Green Building Council (GBC), which comprises over 70 independent nonprofit organizations. However, certain countries opt to adopt established accepted systems, while others opt to develop their own SCSs. According to Sánchez Cordero et al. [16], the most utilized SCSs include BREEAM (65%), the pioneering system, followed by the French HQE certification (13.58%), the German DGNB certification (6.49%), the globally prominent LEED (5.46%), and others with less than 5% utilization. CASBEE, from Japan, is also acknowledged by many authors as a prominent global SCS.

In the next subsections, LEED, BREEAM, and DGBN are described. Table 2 describes the three rating systems' basic information as country of origin, type of application, year of creation and update, and the types of classification.

Table 2. LEED, BREEAM, and DGNB description.

SCS	Country/ Region	Type of Application	Year Creation	Year Updated	Certification Ratings (From Low to High)
LEED	USA	D + C (Building Design and Construction), Interior Design and Construction (ID + C), Building Operations and Maintenance (BO + M), Neighborhood Development (ND), Homes, Cities, and Communities, LEED Recertification, LEED Zero	1994	2019	Certified (40–49); Silver (50–59); Gold (60–79); Platinum (80–125)
BREEAM	UK	New Construction: Infrastructure, Communities, In-Use, Refurbishment	1990	2021	Pass (>30); Good (>45); Very Good (>55); Excellent (>70); Outstanding (>85)
DGNB	Germany	Existing Buildings, New Construction, Interiors, Districts	2007	2020	Bronze, Silver, Gold, Platinum

Source: authors based on LEED, BREEAM, and DGNB [42–44].

2.2.1. LEED

LEED stands as the universal benchmark for assessing the design, construction, and operation of high-performance green buildings. Across the past 18 years, successive iterations of LEED have continuously driven growth in the global green building sector. This momentum has led to over 93,000 projects being registered and certified, encompassing a total area exceeding 19 billion square feet worldwide [42].

The LEED for Building Design and Construction (LEED BD + C) has a variety of options available to suit every project, from a specialized solution to address specific requirements to choosing between New Construction and Major Renovations [42]. The LEED v 4.1 BD + C has nine different categories with some prerequisites and other credits to score, described as: Integrative process; Location and transportation; Sustainable Sites; Water efficiency; Energy and atmosphere; Materials and resources; Indoor environmental quality; Innovation; Regional priority.

2.2.2. BREEAM

BREEAM stands as the foremost scientifically grounded set of validation and certification systems for promoting sustainability in the built environment worldwide. Since 1990, BREEAM's independently certified standards have been instrumental in enhancing the performance of assets at every phase, spanning from design and construction to utilization and renovation. Millions of structures around the globe are enrolled in striving for BREEAM's comprehensive methodology to attain goals encompassing ESG, health, and net-zero objectives. This initiative is under the ownership of BRE, a purpose-driven organization with a rich legacy of over a century in building science and research [43]. The major categories measured by BREEAM are Energy; Land use; Materials; Pollution; Waste; Water; Health and wellbeing; Transport; Management; and Innovation.

2.2.3. DGNB

DGNB, which stands for the German Sustainable Building Council, is an autonomous nonprofit organization that was established in 2007. It has evolved to become the largest network for sustainable buildings in Europe. The DGNB certification system is designed to showcase the practical viability of transformation, be it on a modest or expansive scope. Serving as a tool for planning and optimizing the evaluation of sustainable structures, interiors, and communities, it contributes to elevating genuine sustainability in construction endeavors. To date, over 10,000 projects in approximately 30 countries have received recognition from the DGNB [44]. The DGNB system is based on the following criteria: Environmental quality; Economic quality; Sociocultural and functional quality; Technical quality; Process quality; and Site quality.

3. Methods

To accomplish the study's goals, the methodology is divided in four stages: the first one involves analyzing existing rating systems through a qualitative examination of the literature. The second involves categorizing rating systems into internationally recognized rating systems. The third stage involves exploring, comparing, and analyzing the different rating systems by a set of case studies through their overall characteristics, average scores, assessment criteria, and categories. Finally, the last step is to identify and explore similarities and differences among the rating systems based on the indicators of energy efficiency from a previous study by Cai et al. [45]. A description of the research methodological stages is presented in Table 3.

Table 3. Methodology stages.

Methodology Stage	Methodological Decisions	Description/References
Literature review	Analyzing existing rating systems through a qualitative examination	Bavaresco and Ghisi [37]; Mattoni et al. [40]; Jiménez-Pulido [41]; Sánchez Cordero et al. [16]; Bernardi et al. [17]; Zuo and Zhao [18]; Ferreira et al. [19]; Ali and Nsairat [20].
Rating systems	Internationally recognized rating system	"LEED v4.1 Building Design and Construction" guide dated July 2023, "BREEAM International New Construction Version 6.0" dated December of 2021, and "DGNB New Buildings Criteria Set Version 2023 International" [42–44].
Case studies	Comparison and analyses Overall characteristics, average scores, assessment criteria, and categories	Eight case studies from the U.S., Brazil, and Europe (Germany, the Netherlands, and the UK) were chosen based on their number of certifications, market growth, and potential according to the characteristics to be an office block constructed or renovated after 2014 with good final ranking classifications. Case studies are supported by the literature: Leal Filho [46]; Wang et al. [47]; Li et al. [48].
Discussion	Identifying and exploring similarities and differences Finding strengths and weaknesses	Cai et al. [45]; Ferreira et al. [19]; Happio and Viitaniemi [49]; Suzer [50]; Bernardi et al. [17]; Varma and Palaniappan [51]; Hamedani and Huber [52]; Park et al. [53]; Zimmermann et al. [54].

Source: authors.

To obtain updated data about the rating systems chosen in this study, the user manuals for LEED, BREEAM, and DGBN were collected from their official websites online. The most recent manual's version of the method designed for new office buildings includes the "LEED v4.1 Building Design and Construction" guide dated July 2023, "BREEAM International New Construction Version 6.0" dated December of 2021, and "DGNB New Buildings Criteria Set Version 2023 International" [42–44].

Energy holds a significant position across assessment methodologies due to its significant environmental footprint and indispensable role in the construction sector. Consequently, there has been a notable focus on developing methodologies for evaluating energy indicators [45,55]. The key criteria to identify indicators of energy efficiency are based on previous studies [45,56,57] and can be described as seven categories: 1. Energy Performance (EP); 2. Active Design (AD); 3. Renewable Energy (RE); 4. Metering; 5. Commissioning, Verification, and Maintenance (CVM); 6. Passive Design (PD); and 7. Reduction in Carbon Emissions (RCE).

The building type to search was chosen based on Gangolles et al.'s [58] study that concluded that there is a growing body of research utilizing energy performance certificate databases; however, there remains a limited understanding of energy consumption in office spaces. The studies by Armitage et al. [59] and Hjortling et al. [60] are the only studies referenced that conducted thorough analyses of final energy consumption within the office sector in England and Wales and in Sweden, respectively.

The case studies were selected from the rating systems' websites. The selection of these cases followed the criteria indicated below:

(1) Office type: selection limited to office blocks, defined as large buildings primarily designed for public housing or commercial offices. Offices situated at street level, those mixed with residential units on higher floors, and offices within industrial buildings, which are either inside of or adjacent to structures used for industrial activities, were excluded from the selection;
(2) Construction or renovation period: after the year of 2000;
(3) Location: North and South America (USA and Brazil) and Europe (Germany, the Netherlands, and the UK);
(4) Good final ranking classification: gold or platinum (LEED and DGNB), excellent or outstanding (BREEAM).

4. Results

4.1. Description of Indicator's Analysis

In Table 4, the content of the category types of LEED, BREEAM, and DGNB are described and compared according to energy efficiency indicators suggested by Cai and Gou [45].

Table 4. LEED, BREEAM, and DGBN comparison to energy efficiency indicators.

Indicator Types	LEED v4.1 BD + C	BREEAM	DGNB
Energy Performance	✓	✓	✓
Active Design	✓	✓	✓
Renewable Energy	✓	✓	✓
Metering	✓	✓	✓
Commissioning, Verification, and Maintenance	✓	✓	✓
Passive Design	✓	✓	✓
Reduction in Carbon Emissions	✓	✓	✓

Source: Based on Cai and Gou [45]. Legend: ✓ includes indicator in the rating system.

Despite the potential to earn nine credits under LEED, this research primarily focuses on analyzing the Energy and Atmosphere category, which holds the most significant relative weight, accounting for 30% of the total score. This category includes requirements such as Fundamental Commissioning and Verification, Minimum Energy Performance, Building-level Energy Metering, and Fundamental Refrigerant Management. Additional credits are available for Enhanced Commissions, Optimized Energy Performance, Advanced Energy Metering, Demand Response, Renewable Energy Production, Enhanced Refrigerant Management, Green Power, and Carbon Offsets [42]. In contrast, BREEAM's energy criteria, which constitute 16% of the overall score, encompass Reduction of Energy Use and Carbon Emissions, Energy Monitoring, External Lighting, Low-Carbon Design, Energy-Efficient Cold Storage, Energy-Efficient Transport Systems, Drying Space, and Flexible Demand-Side Response [43]. DGNB, on the other hand, differs in its approach, focusing on categories such as the Sociocultural and Functional Quality and Technical Quality. These include aspects like Thermal Comfort, Indoor Air Quality, Acoustic Comfort, User Control, Quality of Indoor and Outdoor Spaces, Safety and Security, Design for All, Sound Insulation, Quality of Building Envelope, Use and Integration of Building Technology, Ease of Cleaning Building Components, Ease of Recovery and Recycling, Emissions Control, and Mobility Infrastructure [44]. Notably, the categories with a higher relative weight in DGNB are "Environmental Quality", "Economic Quality", and "Sociocultural and Functional Quality", each contributing equally to 23% [19].

Comparing the rating systems with the indicators proposed by the energy efficiency methodology [45], it is clear that all of them are covered by certifications. Energy performance is analyzed by the three rating systems mentioned to ensure the optimal functioning of a building's energy system. It is essential to conduct regular and continuous energy efficiency initiatives to assess the actual patterns of energy consumption within a structure [61]. The objective of building energy analysis is to verify energy consumption performance, conduct system comparisons, and discern potential alternatives for improving the structure [61]. For an extended period, policies and strategies aimed at enhancing building energy performance and mitigating building energy consumption have consistently emphasized technological innovations and advancements [62]. The European Directive 2002/91/EC [12], known as the Energy Performance Building Directive (EPBD), underscores the influence of buildings on long-term energy consumption. It advocates that new buildings should adhere to minimum energy performance standards customized to the specific characteristics of the local climate. In the United States, ASHRAE 90 was a voluntary and nationally agreed-upon standard that established the minimum energy efficiency criteria for buildings. In 2001, this standard underwent division, resulting in the ASHRAE 90.1 Energy Standard for Buildings [31].

Achieving building energy efficiency involves the adoption of passive and/or active technologies [63]. Active design encompasses solutions optimizing the building systems, such as heating, ventilation, HVAC, lighting, and others building services applications. In contrast, passive strategies aim to reduce reliance on active interventions, enhancing energy efficiency through architectural elements like building envelopes, roofs, shape, and layout, while considering structural constraint [64]. This research examines the integration of passive and active design in the LEED, BREEAM, and DGBN rating systems, aligning with numerous green and sustainable design guidelines [57,64–66].

Ferreira et al. [67] studied the role of the weighting process in attaining the net-zero-energy building standard through an examination of two Portuguese case studies. The results demonstrated that the ultimate classification aligns both qualitatively and quantitatively across four tools. Nevertheless, it remains uncertain whether these tools specifically emphasize passive design as the principal solution for achieving efficient net-zero-energy buildings (nZEBs). In addition, Chen et al. [64] also emphasized the need for a more precise definition and the consideration of passive design strategies in this context. However, it is crucial to acknowledge that passive solutions, including daylighting and natural ventilation, as mentioned before, exhibit sensitivity to climatic and outdoor conditions, thereby imposing some limitations on their applicability [65,68–70].

Renewable Energy as well as Metering and Commissioning, Verification, and Maintenance are the indicators mentioned that are related to the type of energy a building is using and the technologies and systems used to verify the results of the building as time passes by, and LEED, BREEAM, and DBGN consider them. The implementation of building energy metering serves as a valuable source of information for stakeholders, providing insights into the operational performance of buildings [71]. Analytical insights derived from these data can be leveraged to enhance overall performance. The integration of a comprehensive system for energy metering holds the potential to engage all stakeholders, including occupants, property owners, and energy managers, in collective efforts to put energy-saving initiatives into effect [72]. Many factors drive the installation of meters and sensors in buildings, with the predominant aim centered on enhancing energy management within the structure. The primary objective is to systematically identify and realize potential energy and cost savings, as well as to validate achieved savings [73].

The reduction of carbon emissions is the last indicator and is part of the three rating systems' prerequisites. Lu and Lai [74] reviewed the carbon emissions of commercial buildings and highlighted important aspects, given that carbon emissions from buildings predominantly result from energy utilization [75]. According to Subramanyam et al. [76], the most effective road for carbon mitigation should be the control of energy consumption. Beyond initiatives like providing occupant training in energy efficiency or offering incentives to tenants for energy conservation [77,78], empirical research supports the effectiveness of monitoring indoor CO_2 concentrations as a valuable measure [77,78].

4.2. Description of the Case Studies

This section presents the description of eight case studies chosen according to the criteria to be an office block constructed or renovated after 2014 with good final ranking classifications. Figure 2 presents two examples in the United States, two examples in Brazil, and four examples in Europe.

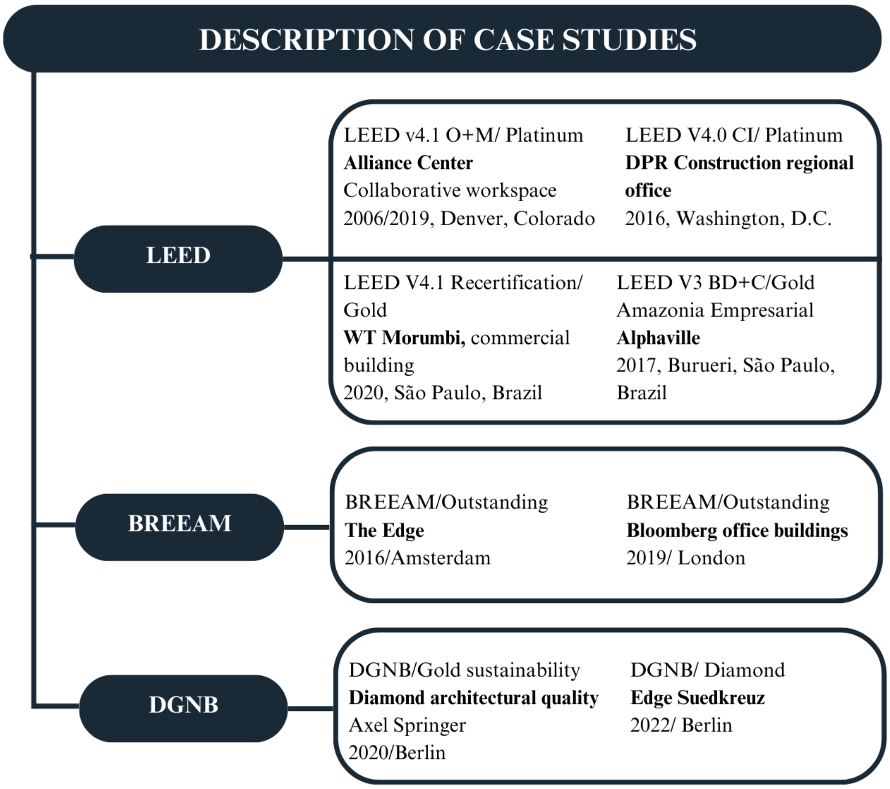

Figure 2. LEED, BREEAM, and DGBN descriptions of case studies [79–86].

4.2.1. LEED

The analysis of the study cases rated by LEED involves two examples in the United States and two examples in Brazil. The first one is classified with a Platinum score in 2019 in Operations and Maintenance (O + M). Located in Denver, Colorado, the Alliance Center is a collaborative workspace with a mission-driven nonprofit for like-minded organizations focused on sustainability solutions. They lead in building certification and LEED performance, advancing a healthy planet, strong democracy, inclusive communities, and a thriving economy while supporting the aim of decreasing the city greenhouse gas emissions. The building has a long history of LEED certification, starting in 2006, and improving its results through the years. Regarding energy efficiency, some strategies used can be highlighted; for example the center uses submeters on each floor to track power usage by load type. These data enable them to work with tenants to reduce consumption compared to previous months and other floors. In addition, The Alliance Center hosts an annual Earth Day event. During this event, elevator access is voluntarily restricted, encouraging participants to use the stairs. Furthermore, strategies using high-efficiency and smart heating and cooling systems; energy usage through renewable energy credits; use of natural light, occupancy light, and heat sensors; as well as Direct Current (DC) charging station and microgrid power generated by solar panels are also part of the accomplishments [79].

The second LEED example in North America called the DPR Construction regional office is in Washington. With a Platinum classification, a goal to not only achieve net-zero energy (NET) but also add to the company's culture a conducive and cost-effective work environment with a balance between functionality and other considerations was summarized in the owner's project requirements (OPR) document. It defined four goals: workspace of the future, sustainability, data-driven decisions, living laboratory. They measure the efforts by the Leesman Index, the most extensive independent database of workplace effectiveness information. To achieve the NET goals, it has a 141 kW rooftop photovoltaic (PV) system combined with a comprehensive lighting system that incorporates motion sensors, photocells, and automated dimming, maintaining consistent lighting levels throughout the day. The selected mechanical ventilation system was an exclusive outdoor air system (DOAS) with a heat recovery chiller. In terms of electrical strategies, the emphasis was on enhancing lighting to complement the daylighting fixtures. Additionally, receptacle controls were implemented to minimize the phantom load from equipment. The office is truly committed with integrating their employees to sustainability, as they use a project dashboard screen. This screen offers up-to-the-minute data concerning energy and water usage, along with the energy generated by the photovoltaic array [80].

In Brazil, a Silver example is WT Morumbi in São Paulo with two towers and 33 floors of office spaces, designed to be a landmark and an example of sustainability in the city. The building implemented various strategies to maximize its natural resource efficiency both during and after construction. Notable achievements include water savings of over 40% and a 10% decrease in energy usage. The façade of the building is made of reflective glass, a type of material that harnesses natural light while simultaneously reducing heat entry. This results in a reduced reliance on artificial lighting and the air conditioning system, leading to energy savings that are always considered during occupancy. For the optimal operation of the air conditioning system, the VRF format was chosen, utilizing a water condensation system and evaporative units to be installed by users. This methodology enables temperature control by zones, meaning different areas can have different temperatures, and the air conditioning can only be used in the areas that are actively being utilized. This system, in conjunction with the work performed by the reflective façade, is expected to significantly reduce energy consumption [81].

Another Brazilian example is also in São Paulo, a building called Amazonia Empresarial Alphaville, a Gold LEED BC + C certification in 2017. The building, with 18 floors, has some features that reduce operating costs, offer environmental respect, as well as provide greater comfort and efficiency for the businesses that settle there. As for examples regarding energy efficiency, several can be mentioned: the high-performance laminated glass providing ample natural light and low thermal absorption; a lighting design project minimizing the impact of lighting on the neighborhood and optimizing electrical consumption; maximized energy efficiency in the air conditioning system; a CFC-free air conditioning system; preferred parking spaces for low-emission and low-consumption vehicles [82].

4.2.2. BREEAM

Regarding BREEAM achievements, a notable example is The Edge, an office building located in Amsterdam. This structure exemplifies the seamless integration of vibrant and collaborative workspaces with the highest standards of sustainability. Notably, The Edge not only achieves energy neutrality but exceeds it by generating surplus energy. It utilizes 70% less electricity in comparison to comparable office structures and features a great number of photovoltaic panels on both its roof and south-facing facade. Additionally, the building utilizes an aquifer thermal energy storage system to meet its heating and cooling needs, with a heat pump to further enhance efficiency. The constant monitoring of factors such as occupancy, lighting, humidity, and temperature, among others, ensures optimal performance. Intelligent technology enables real-time adaptation of systems to maximize efficiency based on these measurements. Facade details vary according to orientation, with features like louvers on the south facade providing additional shading akin to sunglasses. Solar panels on the south facade not only contribute to electricity generation but also power electric devices and cars for workers [83].

Another example of BREEAM is the Outstanding Bloomberg, an office building in London and an award winner in 2019. The foundational principle of the building's design centered around rigorous sustainability standards. It can be cited that the Integrated Ceiling Panels represent a groundbreaking fusion of air supply, cooling, lighting, and acoustic capabilities within a forward-thinking design. They seamlessly integrate energy-efficient LED lighting, harnessing the advantages of elevated chilled water temperatures for maximum energy savings. The building's bronze blades are ingeniously designed to open and close, facilitating natural ventilation and fostering a connection to the outdoors. With the inclusion of smart airflow sensors, air distribution is intelligently regulated based on room occupancy and zoning patterns, effectively curbing CO_2 emissions. To further enhance its sustainability, a state-of-the-art Combined Heat and Power (CHP) generation center efficiently repurposes the excess heat produced during this process for both heating and cooling applications, exemplifying a holistic approach towards resource conservation [84].

4.2.3. DGNB

For the German rating system, DGNB, Axel Springer in Berlin is an example of a Gold-level score for the sustainability standards in new construction and Diamond for architectural quality. The building's functionality is centered on both its façade and atrium. The primary office façade employs a space-saving double-skin design, regulating sunlight with silk-screened black glass panels. In contrast, the inner façade incorporates movable panels to facilitate natural ventilation. This dual-façade system optimizes daylight utilization and contributes to excellent energy efficiency. In addition, its double-skin design enables occupants to maximize the duration for which they can rely on natural ventilation year-round. This open airflow circulates from all offices to the central atrium. This method not only improves energy efficiency but also guarantees a comfortable environment for the building's occupants [85].

Edge is the other example of a DGNB Diamond rating in Berlin. The exterior features a grid of lightweight, weather-resistant glass-fiber concrete panels, weighing only 30 kg/sqm, substantially reducing the building's overall weight and carbon footprint. This emphasis on sustainability extends to the construction phase, with a 50% reduction in the use of reinforced concrete compared to that in conventional methods. The project is also registered in the Madaster database, equipped with a material passport for future reuse and recycling, underscoring a commitment to cradle-to-cradle principles and a greener, more sustainable future. Cells, a leading provider of photovoltaic systems, has spearheaded the integration of sustainable technologies in this innovative space. The use of an ETFE cushion roof floods the area with natural daylight, reducing the need for artificial lighting. The Energy Supply Pillars, including Sufficiency, Efficiency, Combined Heat and Power (CHP), and Load Management, form the backbone of the building's energy strategy, ensuring a balanced and efficient power supply. To promote conscious energy consumption, the design creates an environment that encourages users to be mindful of their energy usage. Smart ceilings, responsible for air conditioning in office spaces, are suspended to maximize efficiency [86].

5. Discussion

Looking further into the similarities found in the cases studies and in the indicators, as shown in Table 5, it is possible to notice the use of renewable sources, monitoring systems, heat and air conditioning, daylight, and natural ventilation as common examples of energy efficiency practices in commercial/office buildings. These design and technology strategies can be considered important for a building's performance in terms of its resilience to environmental conditions. These results align with the study of Cai and Gou [45], which focused on findings about green buildings' rating systems for data centers. Some of their results can be compared to those of office buildings as the assessment of HVAC systems, for example. The analysis of their performance to maximize energy efficiency involves implementing and optimizing an energy-saving HVAC design adapted to the scale and specific circumstances [45]. Additionally, the arrangement and zoning of specific spaces need adjustments to enhance the airflow distribution, achieve uniform room temperature, eliminate localized hot spots, and appropriately raise the operating temperature of air conditioners [86]. In addition, LEED, BREEAM, and DGNB incorporate a few requirements focusing on daylight and building code ventilation, also supported by the study by McArthur and Powell [87].

Table 5. Similarities and differences found in the study cases and in LEED, BREEAM, and DGBN indicators and criteria.

Source	Similarities	Differences
Case studies	• Photovoltaic solar panels • Use of track of power • Motion sensors • Use of daylight • Natural ventilation • Combined Heat and Power (CHP/CFC-free air conditioning system	• Leesman Index: the most extensive independent database of workplace effectiveness information [80] • Preferred parking spaces for low-emission and low-consumption vehicles • Aquifer thermal energy storage system • Track parameters including occupancy, movement, lighting intensity, humidity, and temperature • Smart airflow sensors • Glass-fiber concrete panels
Indicators and Criteria	• BREEAM and DGNB focus more on local standards • Lack of occupancy measure in the post construction phase	• More prescriptive approach in LEED • DGBN criteria are different • DGBN can be considered the best Building Sustainability Assessment tool due to its triple-bottom-line approach

	• Refrigerant management/cold storage (LEED and BREEAM) • Verification/monitoring • Building performance • Carbon emissions control	

Source: authors based on case studies and certifications analysis.

Similarities in the assessment frameworks of LEED, BREEAM and DGBN as sustainability assessment methods for retail buildings, which includes offices as a type of building, can be found in the literature in studies by Ferreira et al. [19] and Happio and Viitaniemi [49]. These energy efficiency similarities can be described according to the criteria as refrigerant management/cold storage in LEED and BREEAM, verification/monitoring, building performance, and carbon emissions control in the three rating systems. These findings align with those in Suzer's [50] study that proposed a parallelism between LEED and BREEAM based on an analysis of 20 dual-certified buildings, highlighting a substantial 83% compliance between the two rating systems. Furthermore, all three rating systems undergo periodic revisions to ensure they remain up-to-date and aligned with evolving sustainable standards. This process contributes significantly to the ongoing transformation of the construction market towards greater sustainability.

The differences analyzed in the three rating systems are the lack of occupancy measure in the post-construction phase. This finding can be considered a huge weakness in all three rating systems because it hinders the ability to accurately assess how buildings perform in real-world conditions. Just one LEED example (the DPR Construction regional office) was found in the study cases. It cited the Leesman Index, which effectively shares information about the workplace. Despite this result, Pastore and Andersen [88] emphasized the significance of post-occupancy evaluations for enhancing green building certification systems and regulations, drawing insights from a Swiss office building. Furthermore, the study by Alborz and Berardi [89] indicates that LEED labeling inadequately reflects actual user behavior. In their examination of 100 LEED-certified commercial buildings' energy consumption, Newsham et al. [90] identified key factors contributing to variations between design intentions and post-occupancy results. Variations in occupancy patterns and plug loads, discrepancies between the constructed building and its design, and deviations in the performance of the technologies were highlighted. In addition, most of the energy consumption predication in the design phase is based on simulations, and these assumptions and hypotheses may not align precisely with the actual use of the building by real occupants. Schwartz and Raslan [91] examined the probability of attaining diverse scores through different Building Performance Simulation (BPS) tools including LEED and BREEAM. Despite variations in the projected overall energy demand, the performance enhancement between the 'Designed' and 'Baseline' buildings remained consistent across all three tools, at approximately 3% [91].

When comparing the criteria utilized by each of the three rating systems, the investigation indicates that LEED follows a more prescriptive approach, while BREEAM and DGNB opt for a performance-based approach [87]. The prescriptive approach of LEED provides projects with explicit guidelines and standards, facilitating a clear understanding of the certification requirements. However, this approach might limit flexibility and innovation since projects need to conform to predetermined criteria instead of having the freedom to explore alternative solutions. On the other hand, in the performance-based approach, projects are assessed based on their actual performance across sustainability categories like energy efficiency and indoor environmental quality. This fosters flexibility and innovation, allowing teams to choose effective strategies and technologies. It also encourages ongoing monitoring to ensure that performance targets are met over time. Ultimately, DGNB stands out as a more integrated Building Sustainability Assessment (BSA) method, particularly due to its triple-bottom-line approach, which considers the entire life cycle of the building [53]. This finding is also supported by Bernardi et al. [17], Varma and Palaniappan [51], Hamedani and Huber [52], Zimmermann et al. [54], and Ferreira et al. [19] and can be considered an important approach to embrace sustainability, ensuring environmental responsibility.

An examination of the primary categories reveals that LEED and BREEAM primarily concentrate on the environmental facets of sustainability, having originated as "green building" rating schemes [51]. In addition, Awadh [92] exanimated how rating systems address the three pillars of sustainability. The study concluded that all systems attribute the highest importance to the "environmental pillar," while the "economic pillar" carries the lowest weight. However, in the recent work of Wen et al. [93], there is an observed increase in the importance of the social level along with the economic aspect, while the environmental concern shows a decrease, considering the period from 1990 to 2021. This suggests a shift towards equal importance and weights for all three aspects in the future [19]. Varma and Palaniappan [51] and Zuo and Zhao [18] suggested that to improve the economy pilar, additional indicators might be incorporated to minimize initial building costs. Therefore, upcoming versions of these approaches should focus on assessing the worth of retail buildings concerning their market appeal, longevity, and positive impact on the community through the establishment of pertinent benchmarks [19]. To enhance the economic aspect of rating systems, one approach is to conduct a lifecycle cost analysis of buildings. This involves considering the economic advantages of sustainable choices, such as reduced maintenance costs and increased asset value. Additionally, providing financial incentives or tax credits for sustainable building practices can also contribute to improving the economy pillar.

Findings regarding the strengths and weakness of LEED, BREEAM, and DGBN are shown in Table 6. Besides the examples already mentioned, we highlight contentious findings indicating no discernible distinction in source energy utilization between LEED-certified and traditional buildings [94]. This conclusion is further corroborated by Amiri et al.'s [95] study, which confirms that buildings with a lower level of LEED certification exhibit similar source energy usage patterns to those of non-certified buildings. In situations where a construction project has achieved a heightened level of energy efficiency, LEED permits a scoring allocation process into Energy Atmosphere (EA) or Innovation (INN), as well as other categories contingent upon specific attributes. Given that EA typically entails greater operational and economic expenses for certifying efficiency improvements [96], practitioners of LEED tend to assign their acquired scores to the INN category due to its requirements of fewer documents, less time, and reduced financial investment [97].

Weaknesses of BREEAM include the social and economic aspects and are less explored compared to the environmental pillar [98]. Also, it presents a complex system, which may lead to the displacement of space for more direct tools, particularly in Europe, where intense competition is prevalent [98]. Another weakness is the associated cost, as achieving BREEAM certification often necessitates additional expenses in design, construction, and certification fees [99]. This financial burden may hinder some projects, especially those operating with limited budgets. Additionally, while BREEAM enjoys widespread recognition in specific regions, its global recognition may lag behind that of other rating systems such as LEED [100]. This limited global recognition could restrict its use in international projects, where stakeholders may prioritize certifications with broader acceptance and market appeal. In summary, the assessment of environmental, economic, and social sustainability aspects varies among LEED, BREEAM, and DGNB, posing challenges in comparing the outcomes of building certification [51]. What qualifies as high sustainability in one framework might vary considerably in another due to differences in criteria weighting and assessment methods. Additionally, regional disparities and contextual factors can complicate comparisons, particularly when assessing buildings in diverse geographic or cultural settings. For DGBN, some challenges are due to the manual for new construction which must be formally requested and is not accessible directly through the website [98]. Furthermore, the cost of certification may serve as a barrier for the adoption of this system, and, depending on the nature of the project, it could present a substantial financial burden. This may influence decision-makers to opt for an alternative certification system [98]. Efforts to standardize practices and enhance transparency in assessment methods can mitigate these obstacles and promote the development of more cohesive and inclusive sustainability evaluation frameworks.

On the other hand, these rating systems exhibit numerous strengths in advancing sustainability in the built environment. LEED is globally recognized and offers a comprehensive focus on energy efficiency, indoor environmental quality, and material selection. Some of LEED's strengths can be cited as higher rental value compared to that of uncertified buildings [101] and a sale premium equivalent to 25% [102]. In addition, there is an upward trend in the level of LEED certification attained by buildings [95]. According to Madson et al. [103], achieving higher certification levels in newer versions of LEED has become more challenging. The authors emphasized that regardless of the method used, converted LEED scores showed a positive correlation with time, suggesting that the sustainability of buildings has increased from 2006 to 2017. However, the concentration of certified LEED projects tends to be highest in areas of cities with the greatest economic potential [104]. BREEAM stands out for its inclusion of social factors, promoting community engagement and occupant wellbeing alongside environmental considerations. BREEAM is considered one of the most comprehensive system tools [98] and can play an important role in the design [105]. BREEAM excels in stakeholder engagement, fostering collaboration among project teams, occupants, and communities for a holistic sustainability approach. It also offers flexible versions tailored to specific building types and locations, enabling adaptation to local contexts and regulations [106]. DGBN is the example of the best definition of sustainability [98]. Additionally, the system covers over 60% of the entire German commercial real estate market [107] and enables certification on a global scale with high quality standards [108]. DGNB's holistic evaluation method integrates environmental, economic, and sociocultural criteria, providing a thorough assessment of sustainability. Together, these systems contribute distinctively to promoting sustainable building practices, addressing diverse needs and priorities across the construction industry.

LEED, BREEAM, and DGNB each present unique opportunities and threats in the realm of sustainable building certification. LEED, with its global recognition, offers buildings a chance to showcase their sustainability on an international stage, potentially leading to higher market value and an upward trend in certification levels. However, the complexity and cost of achieving LEED certification, along with the prescriptive approach and discrepancies in energy usage, pose challenges. BREEAM, on the other hand, offers a comprehensive sustainability approach with a focus on stakeholder engagement and flexible versions tailored to different contexts. However, its complexity and cost, limited global recognition, and focus on the environmental pillar over social and economic aspects could hinder its adoption and impact. DGNB stands out for its triple-bottom-line approach, high-quality standards, and integrated assessment method, making it a credible and effective tool for sustainable practices. However, its manual request process, cost of certification, limited global recognition, and emphasis on the environmental pillar present challenges that need to be addressed for wider adoption and impact. Efforts to standardize practices, enhance transparency, and balance the three pillars of sustainability can mitigate these threats and promote more inclusive and sustainable building practices worldwide.

Certification systems play an important role in promoting and verifying the sustainability of buildings contributing significantly to the Green Transition and the circular economy. In particular, certification systems set standards for efficient resource use, including energy, water, and raw materials. By meeting these standards, construction companies can minimize wastage and maximize the use of resources (especially, but not only energy), which is a core principle of the circular economy. Ng et al. [109] conducted a life cycle environmental assessment (LCEA) of green-rated non-residential buildings (NRBs) at different levels, comparing them to non-green NRBs. They found that energy efficiency accounts for up to 19% of the total life cycle energy of green-rated buildings during the building phase, with construction materials contributing 68–74% of this total. The assessment of the circular economy (CE) in construction is still evolving, lacking clear definitions and practical approaches [39]. However, BREEAM-C stands out as a valid framework, integrating circular indicators into green building certification and aligning with CE principles. It effectively identifies benchmark circular practices in construction [110]. Amiri et al. [111] advocated for green building certifications to prioritize sustainable construction materials, considering the growing importance of embodied emissions and carbon neutrality goals.

Renewable energy sources are increasingly significant in the built environment and play a crucial role in sustainability assessments for LEED, BREEAM, and DGNB certification systems. LEED's renewable energy criterion is particularly stringent, requiring stakeholders to generate a portion of their building's annual energy consumption on-site within a 10-year period. This requirement ranges from 20% for on-site generation to 100% for off-site renewable utilization [112]. The aim of this credit is to reduce environmental and economic impacts associated with fossil fuel-based energy sources while promoting the use of renewable energy alternatives. Projects can meet this credit by implementing on-site renewable energy generation, utilizing newly established off-site renewable energy sources, or procuring off-site renewable energy.

Table 6. Strengths and weakness of LEED, BREEAM, and DGBN.

LEED	Strengths	Weakness
	• The energy criterion holds significant importance [113]. • The global number of certified buildings has been steadily rising. • Certified buildings typically incur lower operating expenses [95]. • Certified buildings consume 25% to 30% less energy compared to conventional structures [102]. • There is an increasing trend in the level of certification attained by LEED-certified buildings [95]. • Comprehensive focus: on energy efficiency, indoor environmental quality, and material selection.	• Requires paying additional fees [101]. • Allows an allocation procedure for scores into other categories [96]. • Additional expenses are estimated to range from 2% to 10% [114]. • Approximately one-third of LEED-certified buildings consume more energy than conventional buildings [95]. • Studies have found no discernible difference between LEED-certified and conventional buildings in terms of source energy use [94]. • Buildings with a lower level of LEED certification show no variance from non-certified buildings in their source energy usage [95]. • Some clients prioritize eco-certification and may aim for the lowest level of certification [114]. • The awareness rate among occupants is low [115].
	Opportunities	**Threats**
	• Global recognition: offering an opportunity for buildings to showcase on an international scale. • Market value: higher rental values and sale premiums, indicating a market preference for sustainable buildings [101]. • LEED's Innovation (INN) category encourages projects to explore innovative solutions, fostering continuous improvement in sustainable practices.	• Complexity and cost: especially for projects with limited budgets. • Occupancy measurement: The lack of occupancy measurement in the post-construction phase hinders the accurate assessment of building performance, impacting the credibility of LEED certification. • Discrepancies in energy usage: Some studies suggest no discernible distinction in source energy utilization between LEED-certified and traditional buildings, raising questions about the effectiveness of LEED in achieving energy efficiency goals. • Prescriptive approach: LEED's prescriptive approach may limit flexibility and innovation, as projects need to conform to predetermined criteria instead of having the freedom to explore alternative solutions.

BREEAM	**Strengths** • Plays an important role in the design [105] • System with the most certifications in the world [98] • Considered one of the most comprehensive system tools [98] • Stakeholder engagement: fostering collaboration and awareness among project teams, occupants, and communities, promoting a holistic approach to sustainability [43] • Flexibility: offers different versions tailored to specific building types and geographical locations, allowing for adaptation to local contexts and regulations.	**Weakness** • Social and economic aspects are less explored compared to the environmental pillar [98] • Presents a complex system [98] • Cost: often requires additional investments in design, construction, and certification fees, which may deter some projects, particularly those with limited budgets [99] • Limited global recognition: while BREEAM is widely recognized in certain regions, its global recognition may be reduced compared to that of other rating systems like LEED, potentially limiting its applicability in international projects.
	Opportunities • Stakeholder Engagement: BREEAM excels in stakeholder engagement, fostering collaboration among project teams, occupants, and communities • Community Wellbeing: BREEAM's inclusion of social factors promotes community engagement and occupant wellbeing • Global Scalability: BREEAM enables certification on a global scale with high quality standards	**Threats** • Complexity and cost: BREEAM's complex system and associated costs may hinder its adoption, especially for projects with limited budgets. • Limited global Recognition: While BREEAM enjoys widespread recognition in specific regions, its global recognition may lag behind that of other rating systems, potentially limiting its use in international projects. • BREEAM's complex system may lead to the displacement of space for more direct tools, particularly in regions where intense competition is prevalent.
DGNB	**Strengths** • Best definition of sustainability [98]. • The system encompasses over 60% of the total German commercial real-estate market [44] • Certifies over 80% of new buildings in Germany [44]. • Enables certification on a global scale while maintaining high quality standards [108].	**Weakness** • The guide for new construction needs to be requested and is not available on the website [98]. • Price for certification can be costly [98]. • DGNB assesses thermal comfort through design-phase simulations, aiming to restrict peak air volume for heating and cooling [116].
	Opportunities • Market coverage: DGNB covers over 60% of the entire German commercial real-estate market, indicating a significant market presence and potential for growth. • High quality standards: DGNB enables certification on a global scale with high quality standards • DGNB stands out as a more integrated Building Sustainability Assessment (BSA) method, offering a holistic approach to sustainability.	**Threats** • The cost of DGNB certification may serve as a barrier for adoption, especially for projects with limited budgets. • DGNB's limited global recognition could restrict its use in international projects, where stakeholders may prioritize certifications with broader acceptance and market appeal. • Complexity and transparency: Efforts to standardize practices and enhance transparency in assessment methods are needed to mitigate obstacles and promote the development of more cohesive and inclusive sustainability evaluation frameworks.

Source: authors.

6. Conclusions

In conclusion, the research provides valuable insights for policymakers, researchers, and practitioners involved in promoting energy efficiency in commercial buildings. It not only identifies key challenges and gaps in the existing literature but also suggests avenues for future research, such as a more in-depth analysis of the connections between energy efficiency and the Sustainable Development Goals as well as a focus on the social and economic aspects within rating systems. Overall, the study contributes to the ongoing discourse on energy efficiency and sustainability in the built environment.

The investigation into energy efficiency rating systems, including LEED, BREEAM, and DGBN, offers valuable insights into their structures, criteria, and methodologies. The discussion on similarities and differences between the rating systems sheds light on their strengths and weaknesses. LEED's prescriptive approach, BREEAM's performance-based stance, and DGBN's emphasis on a triple-bottom-line approach contribute to a nuanced understanding of their respective strengths and challenges.

The study underscores the need for ongoing improvements in these systems, including addressing economic indicators, post-occupancy evaluations, and life cycle perspectives. The main trends and recommendations that can be concluded are as follows:

- **Standard practices:** standardizing practices and enhancing transparency in assessment methods are essential steps towards promoting cohesive sustainability evaluation frameworks;
- **Cost considerations:** Conducting lifecycle cost analyses and offering financial incentives for sustainable practices can strengthen the economic aspect of rating systems. Governments may provide more financial incentives, such as tax breaks or grants, to support the adoption of energy-efficient practices in building construction and maintenance;
- **Regular revisions:** periodical revisions would ensure alignment with evolving sustainability standards, driving the construction market towards greater sustainability;
- **Materials and resources:** there will probably be a greater emphasis on the entire lifecycle of building materials and construction practices, assessing their long-term environmental impacts. In this context, the concept of net-zero-energy buildings is likely to gain more attention and require buildings to be highly efficient and powered by renewable energy sources;
- **Occupancy measure:** the absence of an occupancy measure in the post-construction phase remains a notable weakness, hindering accurate assessments of building performance.

Addressing these challenges will be crucial in advancing the effectiveness and relevance of sustainability rating systems in the construction industry around the world.

The future of energy efficiency standards in buildings is likely to be shaped by several key trends and drivers, such as stricter regulations and policies as well as technological advancements, especially in materials science, which may lead to more efficient insulation materials and energy-efficient windows. Also, as the public awareness of climate change and sustainability grows, there will likely be an increased consumer demand for energy-efficient buildings. This could drive more investments in green building technologies and designs.

Overall, energy efficiency in buildings is a key component of broader efforts to combat climate change, promote sustainability, and transition to a cleaner energy future. The various standards can play a key role in this process.

The limitation of this study is that the assessment of Building Sustainability Assessment (BSA) methods involves subjectivity, given the distinct weighting structures of LEED, BREEAM, and DGNB and different criteria within each rating system. The categorization of indicators for this study's comparison aligns with the approach adopted by prior researchers who encountered similar challenges. It is worth noting that this study focused on the comparison of three BSA methods applicable to office buildings, and a more comprehensive understanding could be achieved by analyzing additional methods.

Future studies may focus on the examination of all certification criteria, not only those related to energy, and also apply them in one or more case studies to validate the obtained results. Additionally, future studies could be enhanced by exploring the significance of a comprehensive database that showcases both the projected and actual performance of rated buildings, along with the primary factors contributing to any disparities.

Author Contributions: Conceptualization, B.C.R.; methodology, B.C.R. and A.L.S.; software, B.C.R.; validation, B.C.R.; formal analysis, B.C.R. and A.L.S.; investigation, B.C.R.; resources, B.C.R.; data curation, B.C.R.; writing—original draft preparation, B.C.R. and A.L.S.; writing—review and editing, B.C.R., A.L.S., L.L.B. and W.L.F.; visualization, B.C.R.; supervision, L.L.B. and W.L.F.; project administration, L.L.B. and W.L.F.; funding acquisition, B.C.R. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded in part by the COORDENAÇÃO DE APERFEIÇOAMENTO DE PESSOAL DE NÍVEL SUPERIOR—BRASIL (CAPES)—Finance Code 001.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

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

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