

Article

Operational Carbon Emission Assessment of Buildings: Development and Application of an Electricity Equivalent-Based Calculation Model for Energy-Related Carbon Emissions

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Abstract

Operational carbon emissions of buildings account for more than 25% of global carbon emissions and, generally, over 50% of the total carbon emissions across the whole life cycle of a building. The evaluation and management of carbon emission levels during the operational phase of buildings are at present important tasks for China's construction industry administration departments. This paper analyzes the indicators for evaluating the operational carbon emission levels of buildings and the content of carbon emission calculations, and introduces a specific operation mode for characterizing building energy consumption by the equivalent electricity method from the perspective of building energy consumption statistics. A calculation method for the carbon emission intensity per unit energy consumption of buildings based on the equivalent electricity method is constructed, and its validity is verified through calculations on 15 actual projects. The results show that the variances in carbon emission intensity per unit energy consumption index based on the equivalent electricity method are 0.03, 0.04 and 0.03 for residential, office and venue buildings, respectively, which are far lower than those of the carbon emission intensity per unit building area index (72.79, 123.33 and 153.35) and close to those of the building energy saving rate index (0.02, 0.01 and 0.02). Compared with the building energy saving rate and carbon emission intensity per unit building area, this index can better characterize the degree of building decarbonization and exhibits good evaluation stability across buildings of different functional types. Combined with the building energy consumption quota index, it is conducive to promoting the transformation of the construction sector from dual control of energy consumption to dual control of carbon emissions.

Keywords: building operational carbon emissions; building energy consumption; equivalent electricity approach; building energy efficiency rate



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1. Introduction

The operational energy consumption of buildings is one of the primary sources of greenhouse gas emissions. According to a 2021 report by the United Nations Environment Programme (UNEP), global operational emissions from buildings accounted for 27% of total CO₂ emissions in 2020 [1]. A 2025 report from the China Association of Building Energy Efficiency revealed that China's operational carbon emissions from buildings reached 2.31 billion tCO₂ in 2022, representing 21.7% of the country's energy-related carbon emissions [2]. While China's operational emissions from buildings are lower than the global

average, the absolute volume remains substantial. Given China's 2060 carbon neutrality target [3,4], there remains significant potential for further reduction in operational emissions from buildings.

Operational emissions from buildings are generally recognized as the largest contributor to a building's life cycle carbon footprint. Studies by Cuéllar-Franca & Azapagic [5], Mei Shang & Haochen Geng [6], and Radhi & Sharples [7] on real-world cases found that operational emissions account for 80–90% of total life cycle emissions. Similarly, Kofoworola & Gheewala [8] and Buyle et al. [9] demonstrated, through standardized building studies, that the operational phase contributes 60–90% of a building's total environmental impact. Green buildings exhibit lower operational emission shares due to enhanced energy efficiency and renewable energy integration. Zhao Na et al. [10] analyzed 59 green public buildings and 26 green residential buildings in China, finding average operational emission contributions of 68.86% and 49.6%, respectively. China has progressively reduced operational emissions from buildings through policy measures. Since the 1990s, China's construction sector has implemented multiple energy and emission-related standards [11]. From 2000 to the present, the carbon intensity of building energy use has declined from 20 kgCO₂/kgce to 9 kgCO₂/kgce [2].

To standardize the management and evaluation of building operational carbon emissions, China's Ministry of Housing and Urban-Rural Development (MOHURD) promulgated the national standard General Code for Building Energy Efficiency and Renewable Energy Utilization (GB 55015-2021) in 2021 [12]. The code mandates that new residential and public buildings must reduce their operational carbon intensity by an average of 40% compared to the 2016 energy efficiency design standards, with a minimum reduction of 7 kgCO₂/(m²·a) (Clause 2.0.3). The complementary Standard for Building Carbon Emission Calculation (GB/T 51366-2019) [13] defines operational carbon intensity as “carbon emissions per unit floor area (kgCO₂/m²)”—a metric also adopted in the earlier industry Standard for Computing Green Performance of Civil Buildings (JGJ/T 449-2018) [14]. In addition, diverse evaluation metrics are used in international research. Bastos et al. [15] proposed “annual carbon emissions per floor area” and “per capita annual emissions” for Portuguese residential buildings. Filimonau et al. [16] introduced “carbon emissions per guest per night” for hotels. However, these metrics require careful contextualization due to two key factors, one is geographical disparities, such as Huang et al. [17] finding China's average residential operational carbon intensity (23.8 kgCO₂e/(m²·a)) to be significantly lower than that of other Asian countries (41.9 kgCO₂e/(m²·a)). Another is building characteristics, such as large hotels exhibiting lower emissions per floor area but higher per capita emissions compared to small hotels [16]. The above research shows that, although the carbon emission intensity method of estimating the operational emissions of buildings reflects the energy intensity, and while it is effective for assessing energy efficiency, current indicators fail to capture variations in energy mix (e.g., fossil fuels vs. renewables) and progress in decarbonization (e.g., grid decarbonization or on-site renewable integration).

When buildings consume only electricity for energy use, the operational carbon emission intensity is only related to the power carbon emission factor, and the selection of national or regional carbon emission factors will lead to great differences in results. To improve the accuracy of operational carbon emission intensity calculations for buildings in such scenarios, some scholars and institutions have proposed the adoption of dynamic power carbon emission factors, which may become the norm for building carbon emission calculation in the future. However, at present, a large number of buildings are still at the stage of mixed use of multiple energy sources, especially in China. Therefore, this study focuses on the construction of an operational carbon emission intensity method for complex energy structures.

2. Materials and Methods

2.1. Operational Carbon Emissions of Buildings

There are discrepancies in the statistical boundaries of operational carbon emissions across different standards. Before discussing the carbon emission intensity per unit of a building's operational energy consumption, it is essential to clarify the specific calculation components of a building's operational carbon emissions. Currently, the relevant standards for calculating a building's operational carbon emissions include ISO 21930 [18], ISO 16745 [19], ASHRAE [20], and the Chinese National Standard, the "Standard for Building Carbon Emission Calculation" GB/T 51366 [13].

ISO 21930:2017 Sustainability in Buildings and Civil Engineering Works—Core Rules for Environmental Product Declarations of Construction Products and Services [18] is a widely recognized standard for assessing the environmental impact of buildings throughout their life cycle. It has been adopted by China's Assessment Standard for Green Building GB/T 50378-2019 [21], the U.S. LEED [22], and the UK's BREEAM [23]. The operational phase of buildings in ISO 21930 includes B1 Use, B2 Maintenance, B3 Repair, B4 Refurbishment, B5 Replacement, B6 Operational energy use, and B7 Operational water use. Among these, B1–B5 fall under embodied carbon, while B7 is generally excluded from operational carbon accounting as it lies beyond the scope of environmental impact analysis for buildings. Only B6 (Operational energy use) is considered in operational carbon emissions statistics. For this module, ISO 21930 specifies that it covers energy consumption from technical equipment installed in buildings, including heating, cooling, ventilation, lighting, and domestic hot water systems, as well as other systems such as sanitation, security, fire safety, internal transportation, building automation and control, and IT infrastructure.

In 2017, the ISO also published 16745-1:2017 "Sustainability in buildings and civil engineering works—Carbon metric of an existing building during use stage—Part 1: Calculation, reporting and communication" [19]. This international standard specifically addresses the standardized management of carbon emissions during a building's operational phases, aiming to establish a globally consistent methodology for measuring and reporting greenhouse gas emissions (and removals) from existing buildings.

In 2021, ASHRAE released ANSI/ASHRAE Standard 105-2021: Standard Methods of Determining, Expressing, and Comparing Building Energy Performance and Greenhouse Gas Emissions, which stipulates the general calculation, expression and comparison methods for the operational carbon emissions of buildings. In terms of energy metering, it requires priority to conduct actual measurement through electricity meters, gas meters and heat meters; simulated or bill data can be selected in the absence of actual measurement data. In terms of emission factors, it recommends the adoption of eGrid regional factors (USA) or local power grid carbon intensity, and the use of national average values is not allowed [20]. CIBSE and ASHRAE have a consistent core logic, boundaries and formulas for building operational carbon emissions, but there are differences in emission factors, data caliber and application scenarios.

The Chinese national standard, the Standard for Building Carbon Emission Calculation (GB/T 51366-2019) [13], serves as the fundamental reference for quantifying carbon emissions during the building design phase. This standard defines the scope of operational carbon emission calculations, which includes emissions from HVAC systems, domestic hot water, lighting and elevator energy consumption, renewable energy utilization, and carbon sequestration from the building's green spaces.

As shown in Table 1, operational carbon emissions primarily refer to direct and indirect emissions resulting from energy consumption within the building's functional boundaries (energy flow and usage classifications are illustrated in Figure 1). Although the building

carbon sequestration system can provide partial offsetting effects, its actual contribution remains relatively limited.

Table 1. Comparison of carbon emission standards for building operation.

Stage Codes	Statistical Scope of Carbon Emission from Building Operation	Electricity Carbon Emission Factor	Building Carbon Sink
ISO21930	Carbon emissions from energy consumption of all technical equipment installed in construction works (B6).	Adoption of electricity carbon footprint factor (LCA)	There are considerations, but no details have been specified
ISO16745	CM1 Building related energy consumption CM2 user related energy consumption CM3 building maintenance and refrigerant escape (on the basis of CM1 and CM2) Scope 1: On-site direct combustion (natural gas, fuel oil, biomass, etc.)	Adoption of grid average carbon emission factor	Not consider
ASHRAE	Scope 2: Indirect emissions from purchased electricity and heat (including grid/heat source emission factors) Scope 3: Refrigerant leakage, transportation, etc.	Mandatory adoption of eGrid regional factors (US subregions), national average values not allowed	Not considered
CIBSE	Scope 1: On-site direct combustion (natural gas, fuel oil, biomass, etc.), refrigerant leakage (recommended to be included) Scope 2: Indirect emissions from purchased electricity, heat and cooling capacity (calculated according to regional carbon emission factors) Scope 3: Not included in operational carbon, only considered in whole life cycle assessment	Priority given to UK BEIS regional factors (UK/Europe), support for dynamic marginal factors	Clearly excluded
GB/T51366	Hvac, domestic hot water, lighting and elevators, renewable energy, not considering sockets and miscellaneous energy use	National average values or provincial regional values can be adopted	Greening within the building site

The classification of energy flow and use of carbon emissions from building operation is shown in Figure 1 below:

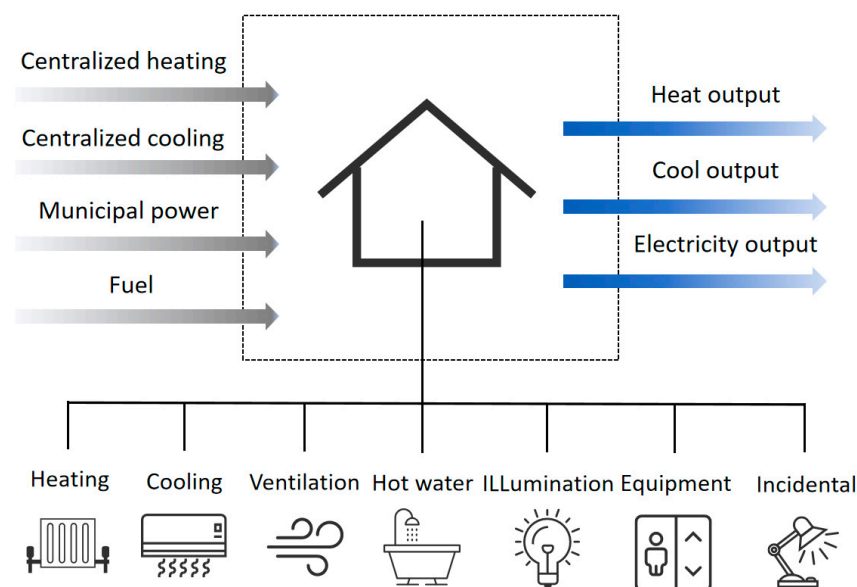


Figure 1. Energy flow and use classification of carbon emissions from building operations.

According to the energy flow and use classification of carbon emissions from building operation in Figure 1, the calculation formula for carbon emissions from building operation can be derived as follows:

$$C_{OCE} = \sum_{i=1}^n (E_i * EF_i) \quad (1)$$

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

The C_{OCE} is carbon emission per unit building area during building operation (kgCO_2/m^2), the E_i is annual consumption of Class i energy for buildings (unit/a), the EF_i is carbon emission factors for Class i energy sources, the $E_{i,j}$ is Class i energy consumption for Class j systems (unit/a), and the $ER_{i,j}$ is Class j systems consume the amount of Class i energy provided by renewable energy systems (unit/a). I represents the terminal energy type of building consumption, including electricity, gas, oil, municipal heat, etc. J represents the type of building energy system, including heating, cooling, ventilation, lighting, domestic hot water system, etc., as shown in Figure 1.

This study takes projects in China as the research object; therefore, in terms of the selection of power carbon emission factors, the national average value is adopted in accordance with national standards.

2.2. Building Energy Consumption

In building energy consumption analysis, commonly used energy statistics and conversion methods include the equivalent calorific value method and primary energy method. The equivalent calorific value method, also known as the “heat method,” only considers the heat quantity contained in energy sources without accounting for differences in energy quality and work capacity. The primary energy method, alternatively called the “equivalent value method,” characterizes secondary energy statistics using primary energy quantities. In China’s energy balance sheet accounting, this method typically converts average coal consumption for power generation into a standard coal equivalent. However, this approach fails to distinguish energy losses occurring during actual power generation, transmission, and consumption processes [24]. The “equivalent electricity approach” comprehensively considers both energy quantity and quality by converting various energy sources into equivalent electricity, reflecting their maximum work capacity under current technological conditions. This method, which unifies different energy forms into equivalent electricity for statistical purposes, has been implemented in China’s building energy efficiency design standards and energy management regulations [25–27]. The basic conversion formula is as follows:

$$Q_e = \eta Q \quad (3)$$

The Q_e is the converted equivalent electricity, in kWh-eq ; the Q is the non-electric energy consumption, in kg , MJ , or Nm^3 ; and the η is the conversion factor for transforming non-electric energy into equivalent electricity. Table 2 summarizes the conversion coefficients for selected energy sources.

Table 2. Equivalent electrical conversion factor of some energy sources [28].

Energy Type	Reduced Unit	Energy Conversion Factor
Electricity	$\text{kW}\cdot\text{h}/\text{kW}\cdot\text{h}$	1.00
Standard coal	$\text{kW}\cdot\text{h}/\text{kg}$	3.14

Table 2. Cont.

Energy Type	Reduced Unit	Energy Conversion Factor
Raw coal	kW·h/kg	2.93
Natural gas	kW·h/Nm ³	5.00
Diesel oil	kW·h/kg	7.81
Gasoline	kW·h/kg	7.89
Hot water (supply/return water temperature) (95/70)	kW·h/MJ	0.064
Hot water (supply/return water temperature) (50/40)	kW·h/MJ	0.039
Saturated vapor (180 °C) (1.0 MPa)	kW·h/MJ	0.110

During the architectural design phase, building energy consumption analysis typically employs energy simulation software, an approach recognized by green building evaluation standards worldwide [19,29]. While countries share similarities in meteorological data selection, geometric modeling processes, and envelope parameter inputs, significant variations exist in software selection and operational schedule settings. For instance, UK regulations specify office equipment power density to be 43.5% higher than the US and 57% higher than Canada; conversely, Canadian lighting power density requirements exceed UK standards by 20%, leading to substantial differences in simulation outcomes [30]. Furthermore, some nations' energy simulations lack comprehensiveness—China primarily focuses on heating, cooling, domestic hot water, lighting and ventilation energy use, while omitting appliance and miscellaneous loads [31]. This incompleteness subsequently affects the accuracy of operational carbon emission calculations, necessitating supplementary analysis during energy assessments.

During a building's operational phase, energy consumption analysis can employ two primary methods: (1) sub-metering, which involves installing dedicated metering devices to monitor real-time energy use across various building systems [32], and (2) data-driven approaches, leveraging historical energy data with machine learning or statistical techniques (e.g., regression analysis or time series analysis) for consumption prediction and analysis—particularly suitable for large-scale building portfolios [33].

2.3. Carbon Emission Calculation of Building Energy Consumption per Unit Based on the Equivalent Electricity Approach

Definition of carbon emissions per unit energy consumption in buildings based on the equivalent electricity consumption—within the scope of operational carbon emission calculations, this metric represents the ratio of a building's operational carbon emissions to its total energy consumption expressed as an electricity equivalent. The unit is kgCO₂/(kW·h-eq), and its calculation is performed as in Formula (4).

$$C_{kce} = \frac{E \cdot EF + E_{pc}EF_i + E_gEF_i + E_pEF_f}{E_z + E_R + E_{pc}f_i + E_gf_i + E_pf_i} \quad (4)$$

The C_{kce} is carbon emissions per unit energy consumption in building operations, in kgCO₂/(kW·h-eq). The E is purchased electricity consumed by building operations, in kW·h. The EF is the carbon emission factor for electricity input from outside the building, in kgCO₂/(kW·h). The E_{pc} is the total amount of coal consumed by the buildings to be converted into standard coal, in kgce. The E_g is the total amount of gas consumed by buildings, m³. The E_p is heat, cooling and other non-electric energy sources purchased from outside the building, in kJ. The EF_f is the carbon emission factor of the quantity of cooling purchased from the outside of the building, and is calculated according to the energy

use type and energy use of the cooling source, in kgCO₂/kJ. The E_R is the conventional energy substitution of renewable energy in buildings, in kW·h. The E_z is the total building electricity demand, including external input of electricity and the use of the building's photovoltaic power generation, in kW·h. The f_i is the equivalent electricity approach; the energy conversion coefficient of type i energy is selected according to Table 2.

Since renewable energy systems produce zero carbon emissions (though some systems still consume grid electricity, resulting in indirect emissions), the numerator in Formula (4) excludes this portion of energy consumption. However, the denominator should account for both the electricity consumption of renewable energy systems and their conventional energy displacement, while avoiding double counting. The calculation of conventional energy displacement may refer to the Chinese National Standard "Evaluation Standard for Application of Renewable Energy in Buildings" GB/T 50801-2013 [34].

Taking solar thermal utilization as an example, the conventional energy replacement amount of renewable energy is calculated by Formula (5).

$$Q_{tr} = \frac{Q_{nj}}{q\mu_t} \quad (5)$$

The Q_{tr} is the quantity of conventional energy substitution by the solar thermal utilization system (kgce). The Q_{nj} is the annual heat gain of the solar collector system (MJ). The q is the calorific value of standard coal (MJ/kgce); q can be taken as 29.307 MJ/kgce. The μ_t is the operational efficiency when using conventional energy as a heat source, selected according to project design documents.

2.4. Data Sources

The data for this study was derived from the public carbon-neutral building certification program launched by the China Urban Research Association. We collected 15 actual design or operational cases during the period from 2022 to 2024, covering three major climate zones: cold regions, hot-summer and cold-winter regions, and hot-summer and warm-winter regions. The relevant data are available on the official China Carbon Neutral Building website. All design details and data usage information contained in the public project materials have obtained authorization from the project principals or designers.

3. Results

The 15 projects include 3 residential buildings (Case 5, Case 7, and Case 12), with the remainder being public buildings featuring functional types such as offices, mixed-use commercial spaces, exhibition halls, and museums. Table 3 not only presents the calculated carbon emission intensity based on the equivalent electricity approach, but also provides the projects' basic information and their converted energy structure according to this methodology.

Table 3. Carbon emission intensity per unit energy consumption and case energy mix based on equivalent electricity approach.

Number	Built-Up Area m ²	Carbon Emission Intensity per Unit Energy Consumption Based on Equivalent Electricity kgCO ₂ /kWh-eq	Energy Mix (Converted Based on Equivalent Electricity Approach)
Case 1	1622.8	0.00	100% photovoltaic
Case 2	14,749	0.45	74.81% grid electricity, 25.19% photovoltaic

Table 3. Cont.

Number	Built-Up Area m ²	Carbon Emission Intensity per Unit Energy Consumption Based on Equivalent Electricity kgCO ₂ /kWh-eq	Energy Mix (Converted Based on Equivalent Electricity Approach)
Case 3	6727.88	0.71	90.36% grid electricity, 9.64% photovoltaic and solar thermal
Case 4	11,936.47	0.35	82.8% grid electricity, 17.2% photovoltaic
Case 5	8537.03	0.35	79.93% grid electricity, 19.08% photovoltaic, 0.99% natural gas
Case 6	29,911.19	0.00	100% photovoltaic
Case 7	156,733.83	0.08	76% grid electricity, 2.58% photovoltaic, 21.42% natural gas
Case 8	283,216.5	0.55	92.68% grid electricity, 2.72% photovoltaic, 4.60% natural gas
Case 9	14,047.17	0.50	79% grid electricity, 21% photovoltaic
Case 10	12,675	0.35	82.63% grid electricity, 17.37% photovoltaic
Case 11	1593.45	0.24	52.38% grid electricity, 43.8% photovoltaic, 3.82% natural gas
Case 12	24,040.81	0.53	79.16% grid electricity, 3.6% photovoltaic, 17.24% natural gas
Case 13	1444.23	0.00	100% photovoltaic
Case 14	104,402.14	0.39	82.21% grid electricity, 4.13% air-source heat pump, 13.66% photovoltaic
Case 15	5987.44	0.38	63.64% grid electricity, 36.36% photovoltaic

Cases 1, 6, and 13 exhibit carbon emission intensities of zero based on the equivalent electricity approach. This results from their building-integrated photovoltaic (BIPV) systems generating surplus electricity relative to consumption. With energy storage system support, these projects achieve zero grid electricity demand, resulting in zero operational carbon emissions. Although actual energy consumption persists, both the equivalent electricity-based carbon intensity and per-unit built-up area carbon intensity register as zero. These special cases align with the definition of a zero-emission building [35].

Concurrently, this study calculates the energy saving rates of case projects (relative to China's current building energy efficiency standards) and determines their carbon emission intensity per unit floor area, with the results presented in Table 4.

Table 4. Computation results of building energy efficiency rate and per-unit built-up area carbon intensity.

Number	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
building energy efficiency rate, %	41.75	31.36	29.06	32.44	61.27	65	38	12.60	34.04	26.00	27.10	27.90	32.04	54.79	55.69
per-unit built-up area carbon intensity, kgCO ₂ /m ² ·a	0.00	7.86	30.61	26.27	21.18	0.00	2.05	74.65	36.55	20.28	26.77	18.90	0.00	17.75	18.54

4. Discussion

Section 3 presents the building energy efficiency rates, carbon emissions per unit floor area, and equivalent electricity-based carbon intensity per unit energy consumption for all 15 projects. As shown in Figure 2, after excluding the zero-carbon buildings (Case 1, Case 6, and Case 13), the equivalent electricity-based carbon intensity demonstrates slightly less dispersion than the per-unit-area carbon emissions. However, this preliminary analysis remains rudimentary. This section conducts an in-depth evaluation of the per-unit-energy

carbon intensity from both sensitivity and stability perspectives, with comparative analysis against building energy efficiency rates and per-unit-area carbon intensity, to validate the rationality and advancement of this proposed metric.

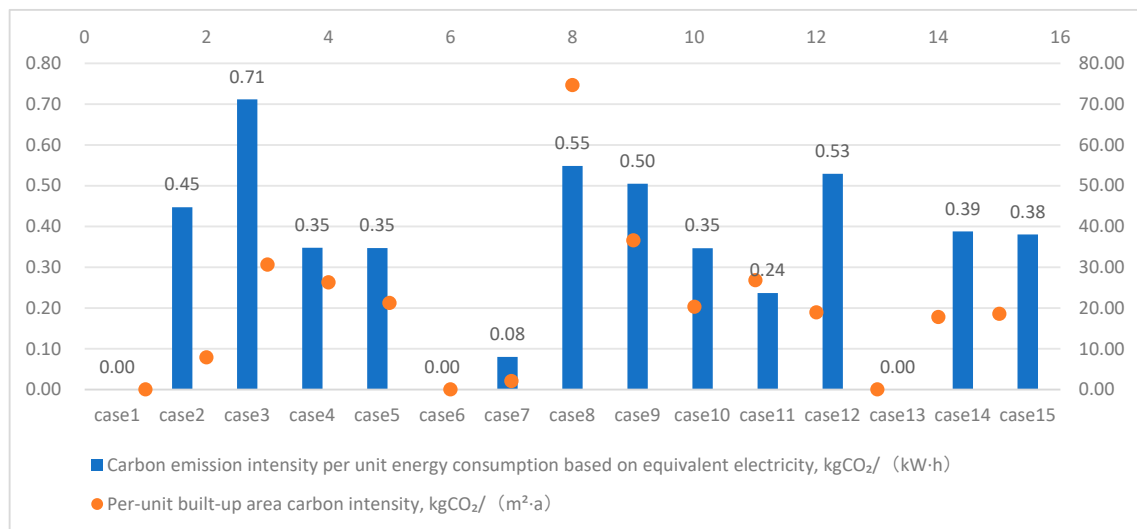


Figure 2. Comparative analysis of dual metrics.

4.1. Sensitivity Analysis of Low-Carbon Energy Structure Transition: Correlation Study

This study employs Pearson correlation coefficient to examine the relationships between renewable electricity substitution rate and three metrics: carbon intensity per unit energy consumption, energy-saving rate, and carbon intensity per unit floor area. As illustrated in Figure 3, the analysis reveals a strong negative correlation ($r = -0.78$, $p < 0.01$, two-tailed) between the renewable electricity substitution rate and carbon intensity per unit of energy consumption, indicating that the carbon intensity metric sensitively reflects the decarbonization effects of the energy structure transition.

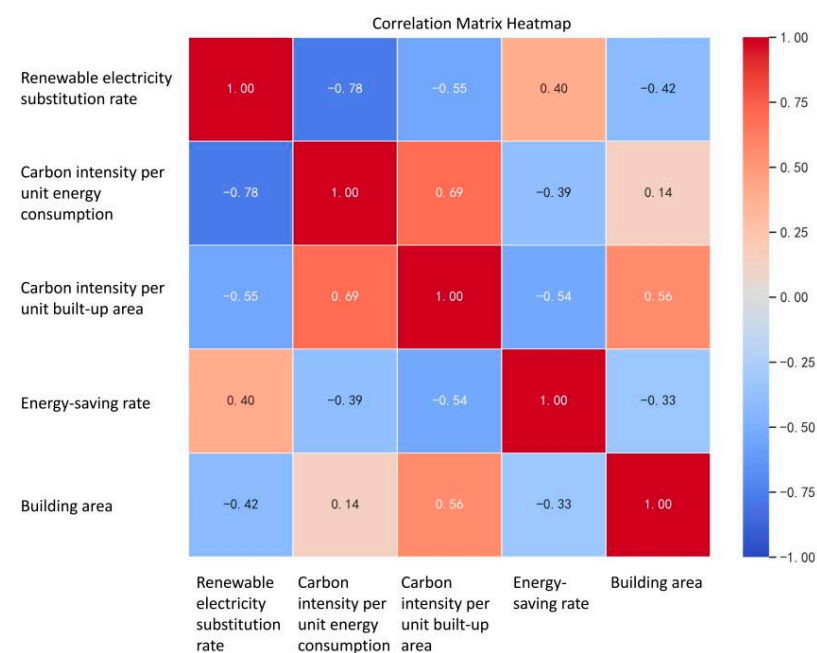


Figure 3. Correlation coefficients between renewable electricity substitution rate and three metrics: carbon intensity per unit of energy consumption, energy saving rate, and carbon intensity per unit of built-up area.

A moderate negative correlation ($r = -0.55$, $p < 0.05$, two-tailed) exists between the renewable electricity substitution rate and the carbon intensity per unit floor area, demonstrating relatively weaker sensitivity to energy structure changes compared to the per-unit-energy metric. The renewable electricity substitution rate shows only marginal positive correlation with the energy saving rate ($r = 0.40$, $p = 0.142$), suggesting that the energy saving rate fails to effectively capture energy structure decarbonization. Furthermore, carbon intensity per unit energy consumption exhibits negligible correlation with building size, confirming its independence from scale effects.

4.2. Cross-Project Functional Typology Comparability: Stability Analysis

The coefficient of variation (mean and variance) for carbon intensity per unit of energy consumption was calculated to verify its consistency across different project types, as detailed in Table 5, Figures 4 and 5. The carbon intensity per unit energy consumption exhibited minimal variance across all three categories, demonstrating high stability among functionally diverse buildings and confirming its suitability as a core metric for cross-type comparisons. In contrast, carbon intensity per unit floor area showed significant variance—particularly in stadium-type buildings—indicating substantial influence from functional typology and usage patterns, and consequently poorer stability in cross-type evaluations. While energy saving rates displayed similarly low variance across categories, their substantial mean differences revealed significant functional dependence.

Table 5. Mean values and variances across functional building typologies.

Type	Residential		Office		Venue	
	Mean	Variance	Mean	Variance	Mean	Variance
carbon emission intensity per unit of energy consumption, ($\text{kgCO}_2/(\text{kWh}\cdot\text{a})$)	0.32	0.03	0.38	0.04	0.12	0.03
per-unit built-up area carbon intensity ($\text{kgCO}_2/(\text{m}^2\cdot\text{a})$)	14.04	72.79	19.79	123.33	8.76	153.35
building energy efficiency rate, %	0.42	0.02	0.38	0.01	0.46	0.02

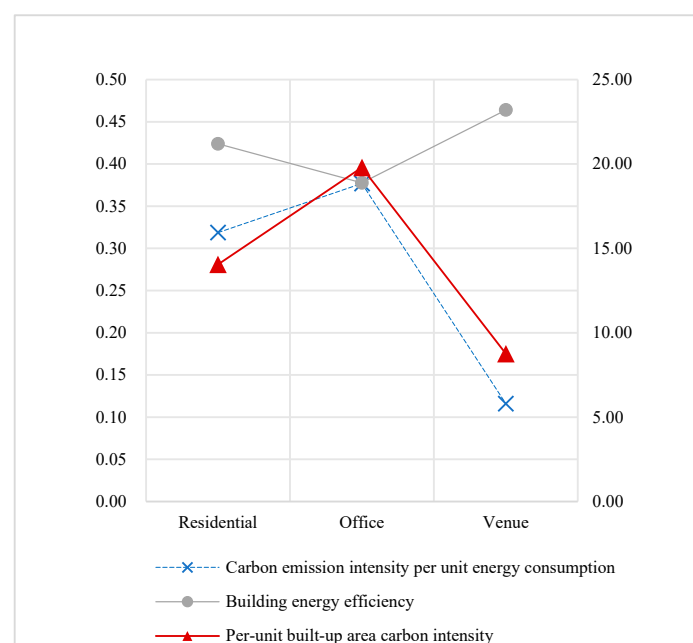


Figure 4. The distribution of the mean of the three metrics.

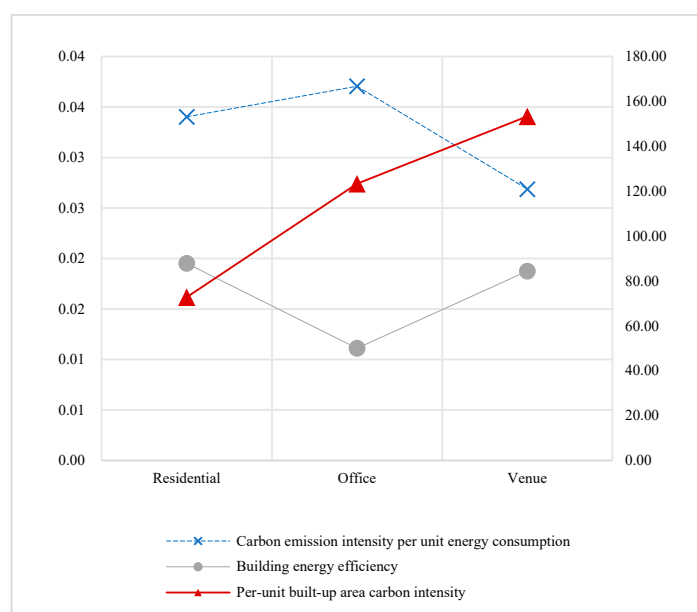


Figure 5. The distribution of the variance of the three metrics.

4.3. Applicability Analysis

Sections 4.1 and 4.2 demonstrate that carbon intensity per unit of energy consumption generally outperforms both energy saving rates and per-area carbon intensity in characterizing operational decarbonization potential. However, this advantage remains statistically limited due to the small sample size. In practice, energy saving rates and per-area carbon intensity remain more prevalent metrics. Therefore, beyond quantitative analysis, this study conducts a comparative evaluation of these three metrics (Table 6), incorporating humanistic, economic and policy considerations to determine their respective applicability scenarios.

Table 6. Metric Characteristics and Application Scenario Analysis.

Metrics	Definition	Points	Application Scenarios	Characteristics
building energy efficiency rate, %	The percentage reduction in building energy consumption relative to baseline consumption	Oriented towards minimizing building energy use	Commonly adopted in current building energy efficiency standards and policies as a self-referential metric	Only reflects relative energy consumption changes without directly indicating absolute carbon emissions levels, highly influenced by baseline energy consumption selection
per-unit built-up area carbon intensity, $\text{kgCO}_2/(\text{m}^2 \cdot \text{a})$	The ratio of a building's annual carbon emissions to its floor area	Achieves carbon reduction by decreasing energy consumption per unit area	Enables cross-comparison among similar building types and aligns well with energy efficiency policies	Significantly influenced by building size, failing to reflect differences in energy mix or operational efficiency
carbon emission intensity per unit of energy consumption, $\text{kgCO}_2/(\text{kWh} \cdot \text{eq} \cdot \text{a})$	The ratio of a building's annual carbon emissions to its total energy consumption	Oriented towards low-carbon energy structure transition	Facilitates cross-type project comparisons and enables integrated building-energy cross-sector assessments	Directly reflects the carbon intensity of energy supply, effectively indicating decarbonization levels of energy mix, independent of absolute building size or total energy consumption scale

5. Conclusions

To achieve its low-carbon society and energy transition objectives, China has mandated increased renewable energy adoption and reduced fossil fuel usage [36]. Building sector policies and standards are further promoting electrification rates and renewable energy integration to realize carbon reduction and ultimate decarbonization. During this transition, diversified renewable energy systems will collectively reshape building energy structures. The equivalent electricity-based carbon intensity per unit energy consumption methodology proposed in this study has demonstrated strong applicability through 15 case validations, with notable innovations in the following aspects:

- (1) This study integrates the equivalent electricity approach with building carbon emission limit management. This approach addresses deviations in operational carbon intensity calculations caused by discrepancies in building area metrics (e.g., gross floor area vs. usable area) and inconsistencies in regional grid emission factors, which previously led to uneven pressure on different building types to adopt renewable energy. By standardizing the evaluation framework, it resolves the lack of cross-functional comparability and simplifies carbon performance assessment while accentuating the decarbonization benefits of renewable energy.
- (2) Carbon intensity per unit energy consumption demonstrates high stability and applicability across functionally diverse buildings, objectively reflecting their carbon performance and serving as a robust core metric for cross-type comparisons. In contrast, carbon intensity per unit floor area is significantly influenced by building function and usage patterns, exhibiting lower stability. While energy saving rates show stability, they remain heavily dependent on building function.

Limitations: The equivalent electricity-based metric overlooks energy efficiency disparities during conversion (e.g., heat pump COP versus gas boiler efficiency) by relying solely on calorific value equivalence. It also excludes integrated decarbonization measures like energy efficiency upgrades or carbon offsetting via sinks. Future research will address these gaps.

Author Contributions: Conceptualization, project administration and writing—original draft preparation, Z.G.; Investigation and methodology, M.L.; Supervision, resources and writing—review and editing, Q.W.; Formal analysis and visualization, X.W. All authors have read and agreed to the published version of the manuscript.

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

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