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Exploring the Applicability of Building Energy Performance Certification Systems in Underground Stations in China

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Abstract: To improve the energy efficiency of underground metro stations, and in view of the absence of a comprehensive energy performance evaluation system for underground stations, this study introduced building Energy Performance Certification (EPC) tools into underground stations and conducted a comparative analysis of their applicability. The findings indicated that due to the unique characteristics of underground stations, China's current EPC system was inapplicable to them. Specifically, (1) for basic items, although evaluation methods were available, due to the limited energy use data for the statistical method, the self-reference method was preferred, but its calculation encountered issues with missing reference values; (2) for prescribed items, the emphasis should be placed on the energy efficiency requirements of energy use systems rather than those of the thermal performance of envelopes; (3) for alternative items, the energy recovery measures related to the heat dissipation of trains and the piston wind should be addressed. Furthermore, a case study was conducted for verification of the proposed energy evaluation method, and the EPC system was updated based on the results of the comparison. The authors hope that this study will help improve China's energy evaluation methods for underground stations and serve as a reference for expanding the EPC system to include public transportation buildings.

Keywords: underground stations; energy performance certification; benchmarking; standards; performance indicators

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1. Introduction

As society continues to develop, the number of metros is increasing around the world. By 2017, metros were available in 178 cities in 56 countries, responsible for delivering a total of 168 million passengers per day [1]. This is especially true for China, where a total of 4681 metro stations have been built in 2020 [2]. Meanwhile, the electricity use of metros has increased enormously with the flourishing development of metros [3]. The energy use of urban rail transit was 17.2 billion kWh in China, of which 8.8 billion kWh were used for non-traction purposes in 2020 [2]. Furthermore, the energy consumed by metro stations represented approximately 30–50% of the total energy used in metro systems [4]. The annual average energy consumption of Underground Metro Stations (UMSs) was also found to be 131–144 kWh/m^2 in China, which was higher than that of traditional buildings [5]. Naturally, it is understandable that the indoor environment and energy efficiency of the UMSs are more difficult to maintain, as these stations are built beneath the ground and serve a large number of passengers [6,7]. Therefore, energy efficiency is urgently needed in UMSs for sustainable development [8–10].

To promote the energy efficiency and optimize the energy use of UMSs, it is essential to understand the status of the station energy use and develop proper methods for energy evaluation. For example, studies investigated the energy use trends of metro stations and the energy use characteristics of the main subsystems of the stations in South Korean cities and Barcelona, respectively [11,12]. In China, the average annual energy use of metro stations was found to be 124.9 kWh/m^2 through large-scale investigations [13]. To restrict the energy use of metro stations in Beijing, Liu et al. proposed quota standards for stations at different service levels based on the statistical analysis of 54 UMSs and recommended that the basic energy quota level for existing stations is 115 kWh/m^2 [14]. Due to the limited data on metro station energy use, Ahn et al. developed a multiple regression model to benchmark the intensity of station energy use using both survey data and Energy Plus software simulation output data [15]. Su et al. established an energy model for UMSs and analyzed the energy-saving potential of different energy saving methods based on simulations [16]. Rajabi et al. designed a framework named 'best in class' benchmarking model based on the analytic hierarchy process to evaluate various energy use systems in metro stations. [17]. Moreover, González-Gil produced a set of performance indicators for assessing and optimizing the energy consumption of urban rail systems [18].

In China, relevant standards or evaluation methods have been promulgated from the national to regional level to guide the energy conversation of metro systems, but these standards primarily focus on the evaluation of energy at the line and network level [19]. Moreover, few metro stations have applied for the Leadership in Energy and Environmental Design (LEED) standard certification, but the current certification framework still follows the existing LEED commercial building evaluation method and does not address the characteristics of UMSs' energy use [20]. Thus, there is an absence of specific energy performance evaluation methods for UMSs. On the other hand, China has been promoting the implementation of building Energy Performance Certification (EPC) schemes since 2008 to help realize the sustainable development of the building sector, and has achieved certain results in pilot cities [21]. The EPC schemes are mature mechanisms that aim to carry out energy assessment activities in buildings and provide useful recommendations on cost-effective measures to improve building energy performance [22,23]. Famous among them are the Energy Star in the United States and the building energy passport system in Germany. However, the types of buildings applicable within the current EPC framework are all aboveground buildings, and underground stations are absent.

Although some studies explore the energy models of UMUs, there is a lack of in-depth research on the overall energy assessment of UMSs. It should not only provide a benchmark model but should also establish a systematic and comprehensive structure that unified the environmental and system parameters that affect energy consumption based on the characteristics of UMSs. Therefore, this research attempts to introduce building EPC mechanisms into UMSs for assessing their energy performance.

The research methods of this work were based on a literature review and a series of semi-structured interviews with relevant stakeholders. The process started by undertaking a review of the literature on the EPC system in China, including academic papers and energy efficiency standards. This led to a preliminary set of comparison contents, such as evaluation items and indicators, for contrastive analysis, subsequently revised and updated through constructive discussions including representative partners from designers, operators and industry experts. A complete set of performance indicators, as well as their value, were agreed amongst all stakeholders and finally validated through their use in the assessment of station energy performance. It should be noted that the methodology presented will remain valid for the further improvement of the EPC framework by different stakeholders. The remainder of this paper is organized as follows: Section 2 provides a detailed overview of the current EPC system in China. Section 3 comparatively analyzes the UMSs and traditional public buildings within the framework of the EPC system. Section 4 attempts to improve the EPC system by discussing five basic questions in EPC development. Section 5 presents a thorough conclusion of the paper.

2. The EPC System in China

In China, the Ministry of Housing and Urban-Rural Development released a series of regulations in 2008 to promote the implementation of EPC schemes [21]. The currently prevailing regulation in China is JGJ/T 288-2012 "Standard for building energy performance certification" [24]. The JGJ/T 288-2012 was designed for both public and residential buildings during the as-built and in-operation phases. In JGJ/T 288-2012, 'energy performance of a public building' means the calculated or measured amount of energy needed to meet the energy demand associated with a typical use of the building, which includes, inter alia, the energy used for Heating, Ventilation and Air Conditioning (HVAC), hot water and lighting [25]. The evaluation system established in JGJ/T 288-2012 includes three main aspects: basic items, prescribed items, and alternative items. The basic items stipulate the whole building-level performance indicators, namely Relative Energy-Saving Rate (RESR) and Energy Use Intensity (EUI). The RESR is used for the asset rating as it refers to the calculated, potential energy performance, and the EUI is used for the operational rating to evaluate existing buildings. The prescribed items refer to the minimum performance requirements for the envelope and HVAC systems that must be met. The alternative items refer to the application of renewable energy and other innovative energy-efficiency measures (EEMs), which can improve the rating level. An example of the Chinese label is shown in Figure 1, which contains a Building Information Box, a Theoretical Rating Box and a Measured Rating Box. The final rating results are presented in each rating box.

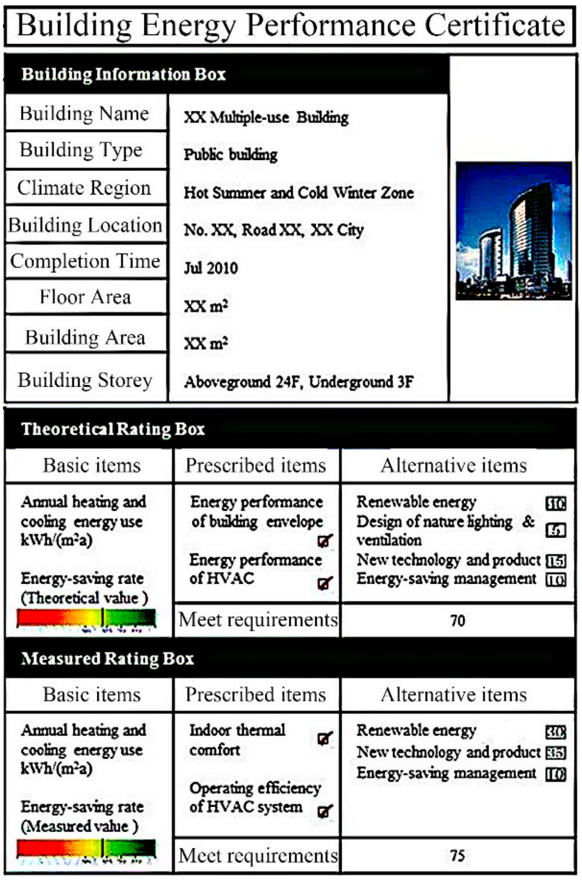


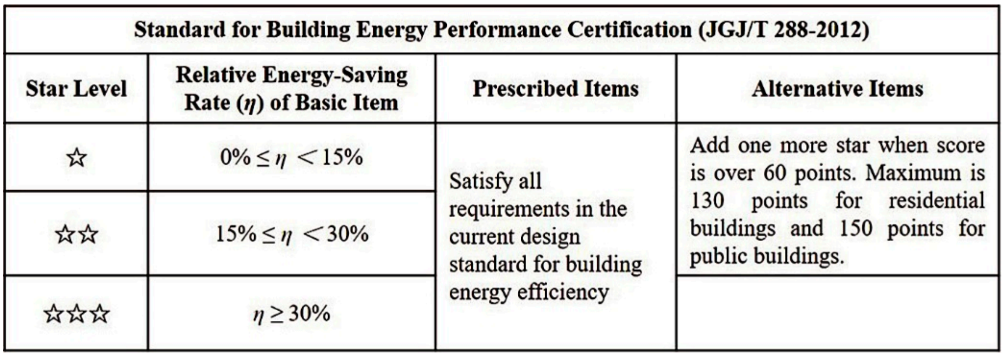
Figure 1. Example of a national energy performance certificate for a public building in China [21].

To calculate the RESR, a self-reference method was used. In this method, a reference building, whose parameters satisfied the conditions and characteristics for the desired level of efficiency in the design standard (generally 50% or 65% energy saving compared with the baseline building), was generated on the basis of an actual building. A comparison of the energy performance with the reference building was made using the following labeling index:

$$\eta = \left(\frac{B_0 - B_1}{B_0}\right) \times 100\%, \tag{1}$$

where η represents the RESR, B_1 represents the EUI value of the building being certificated and B_0 represents the EUI value of the reference building.

In JGJ/T 288-2012, the rating levels of the EPC scheme are shown in Figure 2, and buildings that achieving $\geq$ 30% energy savings compared with reference buildings could obtain the highest three-star level.



Standard for Building Energy Performance Certification (JGJ/T 288-2012)			
Star Level	**Relative Energy-Saving Rate (η) of Basic Item**	**Prescribed Items**	**Alternative Items**
☆	$0\% \leq \eta < 15\%$	Satisfy all requirements in the current design standard for building energy efficiency	Add one more star when score is over 60 points. Maximum is 130 points for residential buildings and 150 points for public buildings.
☆☆	$15\% \leq \eta < 30\%$		
☆☆☆	$\eta \geq 30\%$		

Figure 2. Rating levels of JGJ/T 288-2012.

3. Comparative Analysis

To explore the applicability of building EPC schemes in UMSs for energy conservation, a comparative analysis was conducted between Above-ground Public Buildings (APBs) and UMSs within the framework of JGJ/T 288-2012. It is worth noting that the object area of non-transfer UMSs discussed below was the public areas (hall and platform), as the conditions of the staff accommodation area, which includes the office, control room, washroom, etc., are similar to rooms in APBs.

3.1. Basic Items

The basic items determined the energy indicators and evaluation methods of the certification activities for the APBs. The indicators are RESR and annal EUI, respectively. The RESR is calculated through the prescriptive or simulation method. The prescriptive method provides an algorithm with a set of equations to directly determine the efficiency of the building. The simulation method, on the other hand, makes comparisons between two building simulation models: the proposed building and a reference model (or notional building) outlined in relevant design standards for compliance. EUI is obtained by measurement based on monitoring or energy bills and is compared with statistical benchmarks or ranking. Figure 3 shows the schematic diagram of two types of evaluation method. The former needs a calculation model and parameter values related to energy efficiency design standards, and the latter depends on the development of a database with information on the energy performance of a significant number of similar buildings. For APBs, materials such as modeling procedures, energy efficiency standards and databases are sufficient and complete for the implementation of both types of evaluation.

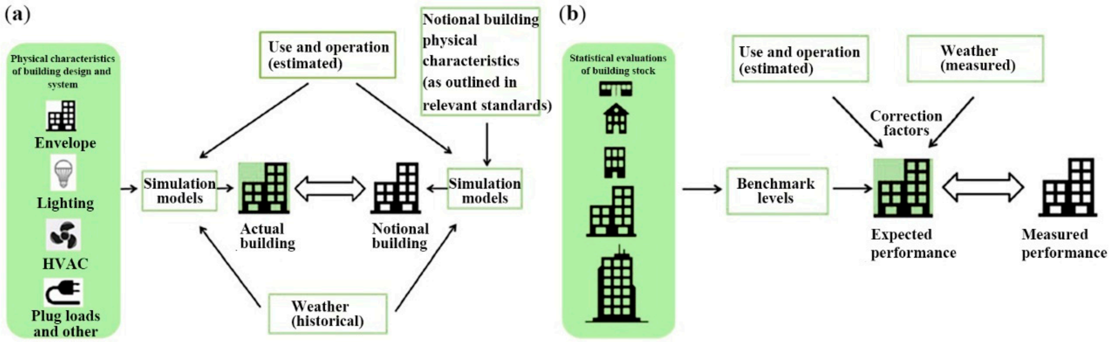


Figure 3. Evaluation of energy performance: (**a**) by simulation for compliance and (**b**) by comparison with statistical benchmarks [26].

As for UMSs, the following are comparatively analyzed on basic items of both asset rating and operational rating. If the asset rating is conducted, relevant energy efficiency standards are needed to determine the reference value of design parameters. The general requirements for parameters in the standards are related to the building envelope, HVAC and lighting systems.

Unlike APBs, the energy performance of UMSs is influenced not only by the thermal characteristics of the building envelopes and the outdoor weather conditions, but also by the surrounding earth [27,28], as shown in Figure 4. Generally, the indoor air of UMSs is heated by a prominent internal heat gain during the operation of stations in the summer daytime [29], and the direction of heat transfer through the envelope is from the station to the earth, which is opposite to APBs. Studies have also shown that heat transfer between the envelope has little effect on the air conditioning load as the damping and delay effect of the earth, and this heat gain is usually neglected in cooling system designs [30,31]. Currently, there are no requirements for the thermal performance of the station envelope in existing energy efficiency standards. Moreover, there is also no shape factor, window-to-wall ratio or shading coefficient for UMSs.

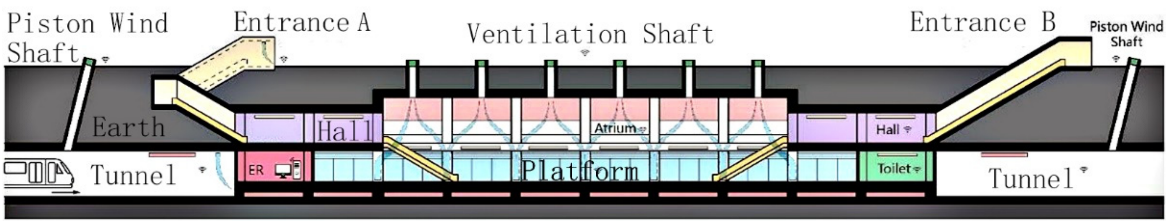


Figure 4. Schematic diagram of a typical UMS [32].

In terms of HVAC systems, four main aspects should be considered, namely indoor air temperature, occupant density, Energy Efficiency Ratio (EER) and operating time. The energy efficiency requirements of these aspects in APBs are all specified in the GB 50189-2015 “Design standard for energy efficiency of public buildings” [33], but are scattered for UMSs in different standards. The functionality of UMSs determines the characteristics of short-term suspension of passengers, and the requirements for their thermal environment are lower than those of public building spaces such as office buildings. According to GB 50157-2013 [34] “Code for design of metro”, it is recommended to maintain an indoor temperature $\leq$ 30 °C for the station halls and $\leq$29 °C for the platforms, with relative humidity between 40% and 70% for both of them, in summer; the temperature should be maintained $\geq$12 °C for both of them in winter, but without any specific humidity requirement. Thus, compared to APBs, the station air temperature also has a baseline for the evaluation of the cooling system. Furthermore, there is usually no need for heating in winter, but just for cooling in summer [35]. Regarding passenger density in public areas, although passenger flow is designed for a future phase, it is a quantity that changes over time and differs from station to station. Therefore, it is difficult to stipulate the number of persons per unit area like rooms of APBs.

For the value of EER, GB/T 51357-2019 "Standard for design of ventilation air conditioning and heating of urban rail transit" [36] added efficiency requirements on multi-split air conditioning and heat pump units used for the staff accommodation area and does not consider the climate zones.

For operating time, UMSs have longer operating hours than APBs, and the operating time is nearly 18–20 h (such as 05: 00–23: 00), which puts forward higher requirements to the HVAC systems of UMSs [31].

With respect to lighting systems, GB 50034-2013 "Standard for lighting design of buildings" gives the Lighting Power Density (LPD) standards for station public areas [37]. The recommended value of LPD for ordinary public areas is $\leq$9 W/m^2, which is less than 8 W/m^2 of the ordinary office rooms in APBs. Table 1 presents a summary of the comparison results of APBs and UMSs within the basic items.

Table 1. Comparison of APBs and UMSs in the basic items.

Classifications		APBs	UMSs
Envelope	Heat transfer coefficient	√	×
	Shape factor	√	×
	Window-to-wall ratio	√	×
	Shading coefficient	√	×
HVAC	Indoor air temperature	√	√
	Occupant density	√	×
	EER	√	×
	Operating time	√	√
Lighting	LPD	√	√

Note: "√" means that there are specified requirements in the corresponding clause, and "×" means that there are no specified requirements.

3.2. Prescribed Items

The prescribed items are the requirements that the building envelope, HVAC systems and lighting systems must meet in accordance with current regulations on building energy efficiency design. In prescribed items, both the asset and operational rating of APBs need to be mandatorily checked item by item according to regulations. The checking procedure includes document review, on-site inspection and performance testing, etc. The main bases for the implementation of the procedures are GB 50189-2015 and JGJ/T 177-2009 "Standard for the energy efficiency test of public buildings".

Table 2 shows the comparison of UMSs and APBs in the prescribed items. It can be seen that, for UMSs, because their enclosure does not involve external windows as is the case for APBs, the airtightness and openable area requirements of the windows are nonexistent. However, in the case of the station equipped with platform screen doors (PSDs), airtightness is required. According to CJJ 183-2012 "Technical code for the platform screen door system of urban railway transit", the gap between the sliding door and the lintel/sill should be $\leq$10 mm, and there should be a sealing brush or other form of sealing in gaps. Moreover, there are no requirements related to thermal bridges in UMSs.

Table 2. Comparison of APBs and UMSs in the prescribed items.

Classifications		APBs	UMSs
Asset rating	Envelope	Requirements for air tightness of exterior windows and glass curtain walls	CJJ 183-2012 for PSDs
		Requirements for openable area of external windows and glass curtain walls	×
		Requirements for insulation on thermal bridges	×
	HVAC	Requirements for proper design of fresh air volume	GB 50157-2013
		Requirements for calculation hourly cooling load	×
		Requirements for heat sources selection	×
		Requirements for selection and performance of air conditioning unit	JGJ/T 288-2012
		Requirements for the water transport factor	GB 50189-2015
		Requirements for the air transport factor	GB 50189-2015
	Lighting	Requirements for the LPD	GB 50034-2013
		Requirements for the energy-saving control strategies	×
Operational rating		Field tests of indoor temperature and humidity	JGJ/T 177-2009
		Field tests of the COP of chiller units and the EER of cooling systems	JGJ/T 177-2009
		Field tests of the power consumption per air volume of the fan	JGJ/T 177-2009

In terms of ventilation, the fresh air volume is required to be at 12.6 $m^3/(person{\cdot}h)$ in the UMS [34]. Regarding requirements for calculating the dynamic cooling load of the cooling system, the current design method just estimates the cooling load under the most unfavorable conditions, and the system should design according to the maximum peak hour passenger flow and traffic density of UMSs [36]. However, calculating the hourly cooling load is difficult due to the unpredictable flow of passengers. On the other hand, unorganized ventilation caused by trains also adds difficulty in calculating dynamic load, which makes it necessary to calculate with the help of simulation software [38–40]. As mentioned previously, there is usually no need for heating in public areas and there are no corresponding requirements for heating in UMSs. For the air-conditioning systems in UMSs, since their forms (which usually adopt a primary air return system) are similar to APBs, and their requirements can refer to the energy efficiency standards of APBs. In terms of operational rating, compared to the requirements of APBs specified in Table 3, UMSs can also be implemented with reference to JGJ/T 177-2009.

Table 3. Comparison of APBs and UMSs in the alternative items.

Classifications	APBs	UMSs
Options	Renewable energy use such as solar energy and geothermal energy	√
	Natural ventilation	Piston wind
	Natural lighting	Light pipes
	Shading measures	×
	Combined cooling heating and power	×
	Cold/heat storage technology	×
	Energy recovery	×
	Total fresh air or changed fresh air ratio operation	√
	Variable water flow of pump or variable air flow of fan	√
	Application of energy management systems	√

3.3. Alternative Items

Different from the prescribed items, the alternative items are the options which can add points by using EEMs in buildings. When the application of EEMs reaches a required level, additional points can be obtained to help increase the star level.

Table 3 lists the comparison between APBs and UMSs within this section. It can be seen that some of the EEMs and corresponding requirements used in APBs are not applicable to UMSs due to their unique geographical conditions, such as the use of natural lighting and shading measures. But UMSs also have unique advantages that they can take advantage of, especially the use of the heat emitted by train movement [41–43] and the piston wind [44–46], for example, the capillary heat exchanger [47], the adjustable platform screen door system [48] and the tunnel wind energy harvesting system [49]. Furthermore, although studies investigated various forms of energy utilization in UMSs, there is still no unified evaluation method in terms of cost-benefit analysis [50]. On the other hand, when considering EEMs related to HVAC systems and building energy management systems, these measures are similar in both APBs and UMSs, and their effect can be judged based on existing standards.

4. Results and Discussion

To find a proper method for comprehensively evaluating the energy performance of UMSs, the EPC system was introduced. However, the existing EPC system focused mainly on APBs and did not address the characteristics of UMSs. Through the comparative analysis, it can be found that some of the benchmark parameters used for evaluation were missing and some of the evaluation content and methods were not suitable for UMSs. Therefore, this section discusses five commonly considered questions [51,52] to improve it so that it is suitable for evaluating the energy performance of UMSs. Furthermore, a case study was conducted for the verification of the proposed; the updated EPC framework was also proposed and further work was also prospected.

4.1. What Should Be Calculated in Order to Assess UMSs' Energy Efficiency?

To assess the energy performance of a building, the first step is the definition of energy performance indicators [53]. The assessment of underground station performance can be conducted at three levels that correspond with the hierarchical nature of station services themselves (i.e., the whole-station level, the system level, and the component level), as shown in Figure 5.

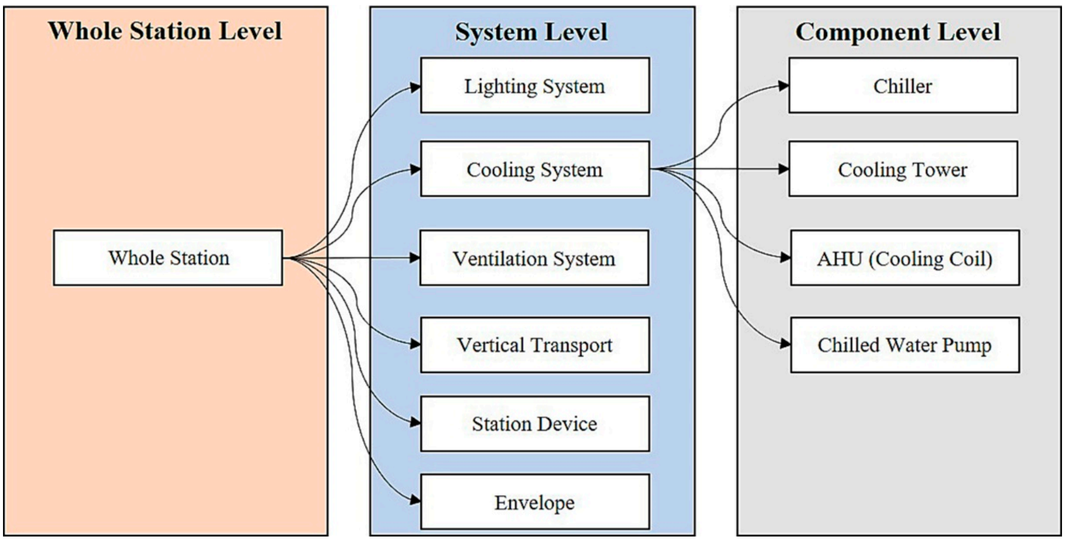


Figure 5. Overview of performance representation at the whole station, system and component levels.

It can be seen that the primary systems and their component in public areas of UMSs were similar to APBs, and it was reasonable to borrow whole building-level performance indicators such as RESR and EUI for certification or rating of UMSs. It is worth noting that there is a clear goal and a set of benchmark regulations for calculation RESR in APBs, namely cutting the energy consumption by 50% or 65% compared with baseline buildings built in the 1980s, but these do not exist in UMSs.

With regard to the system level, some indicators need to be modified. Specifically, indicators related to vertical transport, station devices and envelopes need to be addressed, besides the HVAC and lighting systems. Vertical transportation such as lifts and escalators in UMSs was found to be responsible for approximately 10% of total energy consumption [5,12]. The indicators for its energy performance assessment are regulated in the standard VDI 4707 and ISO 25745. Moreover, this part of energy use can be summarized as passenger flow-related energy use and normalizing by passenger count [18]. Station devices include ticket purchase machines, automatic gate machines, information displays, etc., and consume approximately 5% of total energy consumption [16]. Because the energy use of these devices is small and stable [54], it can be neglected in the evaluation. For the envelope, since there were no requirements for the thermal performance of the envelope, there were also no requirements of relevant indicators, and the value of indicators can default to the common values used in the projects.

The component-level performance indicators were fairly mature due to their use in assessing compliance with building energy codes, and they can also be used in UMSs as they share the same components. Table 4 summarizes the main indicators of different levels for evaluating the energy performance of UMSs.

Table 4. Energy performance indicators for UMSs.

Level.	Name	Common Acronym	Definition	Common Units	Refs.
Whole station level	Energy Use Intensity	EUI	A station's energy use normalized by its size (Usually the total floor area).	kWh/m^2, kBTU/ft^2	[5]
	Relative Energy-Saving Rate	RESR	The ratio of the difference between the annual EUI of the certificate station and the annual EUI of the reference station to the annual EUI of the reference station.	-	[21,51]
System level	Lighting Power Density	LPD	Lighting power per unit station floor area	W/m^2, W/ft^2	[16]
	Energy Efficiency Ratio	EER	The ratio of the cooling capacity to the instantaneous power of the cooling system includes compressors, pumps, and fans.	-	[16]
	Seasonal Energy Efficiency Ratio	SEER	The ratio of output cooling energy from the chiller to electrical input energy considering the varied outdoor air temperature.	BTU/Wh	[55]
	Station/tunnel ventilation energy use	-	Energy used by ventilation systems in a space per m^3 of station/tunnel under predefined operational conditions.	kWh/m^3	[18]
	Station passenger flow-related energy use	-	Specific energy consumption of a single passenger flow-related system for a given operational regime; this comprises lifts, escalators and other passenger conveyor systems	kWh/person	[18]

Table 4. *Cont.*

Level.	Name	Common Acronym	Definition	Common Units	Refs.
Component level	Coefficient of Performance	COP	The ratio of the cooling capacity to the instantaneous power of compressors.	-	[56]
	Integrated Part Load Value	IPLV	A single-number expressing integrated part-load efficiency of air-conditioning or heat pump equipment weighted on different part-load operation conditions. (100%-, 75%-, 50%-, and 25%-part load)	-	[24,55]
	Water Transport Factor	WTF	The ratio of the power consumed by the circulating pump of the cooling system to the cooling load under design conditions.	-	[57]
	Air Transport Factor	ATF	The power consumed by the fans of air-conditioning and ventilation system for transports unit air volume under design conditions.	$W/(m^3/h)$	[33]
	Fan Energy Index	FEI	The ratio of the actual fan efficiency to a baseline fan efficiency, both calculated at a given airflow and pressure point.	-	[8,58]

4.2. How Should Energy Performance Be Obtained?

The current building EPC system in China clarifies the asset rating and operational rating for the energy evaluation of as-built buildings and existing buildings. Among them, the asset rating is mainly based on the implementation of energy calculation, which reflects the difference between the actual building facility parameters and the compliance constraints. The values of the parameters for compliance can be gathered based on the relevant standards in the preparation of the station energy performance assessment, such as GB 50157-2013, GB 50189-2015 and GB/T 51357-2019. Moreover, as the energy efficiency standards for UMSs are not thorough, the calculation values may also refer to the relevant literature. The operational rating is based on actual energy use and on operational and occupancy variables using metering or tests.

4.3. How Should the Limit for Energy Efficiency Be Set?

Building regulations could answer this question by setting the minimum overall requirement for energy performance indicators. There were many differences between UMSs and APBs in energy-efficient regulations, as well as the lack of explicit reference value. Table 5 summarizes the relevant parameter setting values used to establish the benchmark model for a typical non-transfer underground station based on literature and standards.

Table 5. Setting reference values of relevant parameters of a typical underground station.

Elements	Parameter Settings	Refs.
Comprehensive heat transfer coefficient of PSDs	$3\ W/(m^2\cdot{}^\circ C)$	[31]
Infiltration air volume by unorganized ventilation	Due to the different station structures, the parameter setting values are different, see references for details	[31]
Setting temperature in public areas in summer	28 °C	[30]
Heat gain from lighting in public areas	$10\ W/m^2$	[37]
Heat gain from devices in public areas	Obtained from tests or literature	[59]
Heat gain from passengers	182 W/person	[16]
Tunnel air state parameters	Obtained from tests or literature	[59,60]
EER of the cooling system of public areas	Calculated from Equation (A14) in Table A2	[54]

4.4. To What Should the Building Energy Efficiency Be Compared?

If the operational rating is conduct, it is essential to establish an energy consumption database of the similar stations for comparison, categorized, at least, by station size and climate. However, various design differences (such as type of platform doors, number of entrances and climate zones, etc.) have an impact on energy consumption, increasing the difficulty of data collection and classification. Furthermore, at present, actual data on metro operating energy consumption are very scarce [15], and there are few stations equipped with sub-item energy monitoring systems [12]. Due to the difficulty of obtaining sufficient EUI data from the same type UMSs, it is hard to implement the statistical method at present.

Alternatively, asset rating using the self-reference approach, where the actual building is compared with a reference building derived from the actual building according to rules laid down in the energy code, provides a more feasible way for evaluation, which can be preferred in applications.

4.5. What Energy Efficiency Improvements Should Be Recommended?

EPC schemes ought to provide a list of recommendations to encourage building designers and operators to improve the energy performance of their station buildings, and relevant advanced EEMs should be displayed to create public confidence or awareness of the developed systems [61]. Through the certification program, potential energy savings opportunities were possibly identified, and a description of each opportunity, including an estimation of energy savings, budget implementation costs and simple payback, was also provided [52].

4.6. A Case Study

In order to verify the proposed energy evaluation method, a case study was conducted on an underground station in Beijing, China on 28 August 2020. The station is a 2-layer underground non-transfer station with platform bailout doors. The public area of the station covers an area of 4382 m^2 with three entrances. The direct expansion air conditioning system was used for the public area. The volume of mechanical supply fresh air was 39,800 m^3/h.

Before evaluating energy performance, the first step is to prove the precision of the calculation method of the cooling load of the underground station, and then the reference power consumption of the VAC systems can be obtained using the method with the limit value of the energy efficiency indexes. Thus, the thermal environment and energy consumption items were both measured as shown in Figure A1. To investigate the thermal environment in the station, major indoor environmental parameters, including air temperature, relative humidity and velocity, were measured. All sensors have been manufacture-calibrated and underwent zero checks, and detailed information is presented in Table A1. Other information such as passenger volume, train density and equipment power were also recorded, as shown in Figure A2. The train-induced airflow rate for calculating the cooling load was obtained based on the airflow balance of the station [62]. The main formulas and data used for energy evaluation are listed in Tables A2 and A3.

Figure 6 shows the tested and calculated hourly energy consumption of the VAC system, and the accuracy of the calculation method was evaluated by two statistical indicators named the normalized mean bias error (NMBE) and the coefficient of variance of the root mean square error CV(RMSE), respectively. Equations (2) and (3) show the indicators' calculation methods.

$$NMBE = \frac{\sum (V_{actual} - V_{modeled})}{(N-1) \times Mean(V_{actual})} \times 100\% \tag{2}$$

$$CV(RMSE) = \frac{\sqrt{\frac{\sum (V_{actual} - V_{modeled})^2}{N-1}}}{Mean(V_{actual})} \times 100\% \tag{3}$$

where V_{actual} = parameter's measured or metered value for each time step, $V_{modeled}$ = parameter's estimated or modeled value for each time step and N = number of time steps being analyzed during period of evaluation.

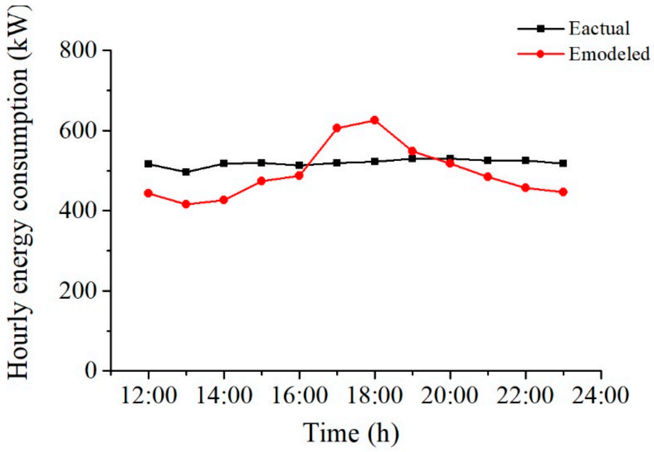


Figure 6. Hourly energy consumption of the VAC system.

According to ASHRAE Guideline 14-2014, a calculation model can be considered calibrated if NMBE < 10% and CV(RMSE) < 30% when using hourly data. The value of NMBE and CV(RMSE) of the cooling load calculation method used in this study was 5% and 13%, respectively; thus, the calculation method was reliable.

In this case study, the total energy consumption of the station consists of the power consumption of the VAC system and the lighting system. The measured and calculated energy of both systems is shown in Table 6. It can be seen that the measured energy value of each system was higher than the corresponding limited value. The RESR value of the station was −9%, which means that the energy performance of the station did not reach the certification level during the test period. It is worth noting that the actual evaluation should be based on annual statistics data, and this case was used to demonstrate the feasibility of the proposed evaluation method.

Table 6. Comparison of measured and limited energy values of the energy use item of the station.

Energy Use Items	Measured Energy Values (kWh)	Limited Energy Values (kWh)
VAC system	6229.1	5909.5
Lighting system	754.6	525.8
Whole station	6983.7	6435.3

4.7. Further Work

Figure 7 illustrates the potential EEMs recommended in UMSs and updates the EPC framework based on the above analysis. The proposed framework expanded the application boundary on the original scope, so that it can be used for assessing the energy use of UMSs. Specifically, for the basic items, the indicators continue to use the original indicators, but due to the limitation of the EUI database of UMSs, the self-reference method, namely the RESR indicator, was preferred. For the prescribed items, the main evaluation objects and corresponding indicators were determined through comparison with traditional buildings. Among them, most of the constraints clauses related to lighting, ventilation and cooling systems can follow the existing requirements, but requirements for the vertical transportation system still need to be further studied. For the alternative items, the study combined the characteristics of UMSs to give relevant EEMs, but the specific cost-benefit relationship of each EEM needs more research.

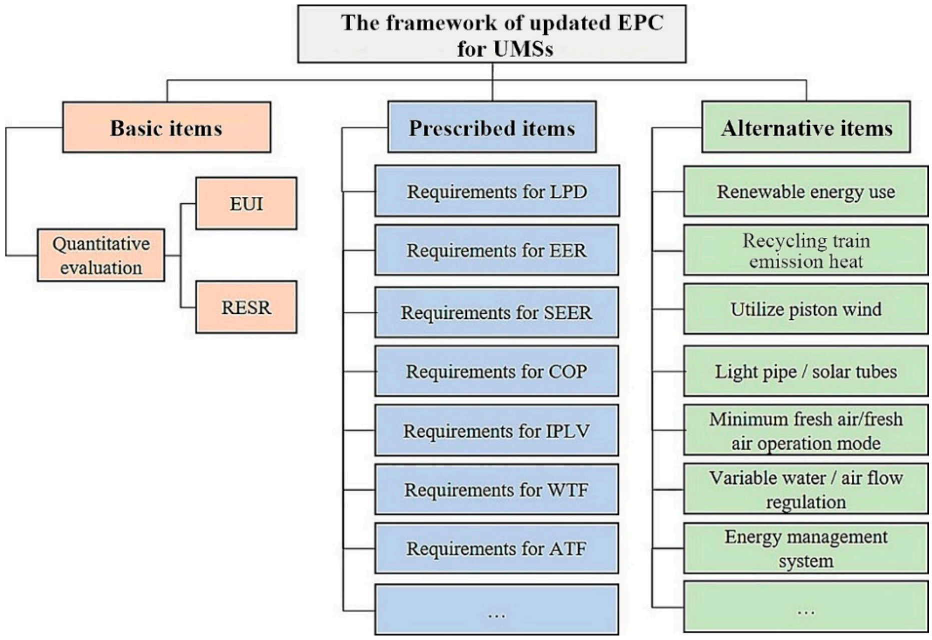


Figure 7. The framework of updated EPC for UMSs.

5. Conclusions

The rapid development of urban rail transit systems has resulted in an increase in the energy consumption of UMSs. The energy conservation of UMSs has become a key issue in the development of sustainable public transportation buildings. To improve the energy management level of UMSs, this research introduced the building EPC system for evaluating UMSs' energy performance and conducted a comparative analysis of UMSs and APBs using JGJ/T 288-2012 to determine the system's applicability.

The findings indicated that due to the difference between UMSs and APBs, it was difficult to apply the existing evaluation system directly to UMSs. The following points exemplified this: (1) for basic items, although the primary evaluation indicators were applicable, due to the scarcity of actual EUI data for statistical methods, statistical or data-driven methods were hard to implement currently and the self-reference method was preferred, but had the issue of missing benchmark parameters when calculating RESR; (2) for prescribed items, UMSs did not emphasize the requirements for the thermal performance of the envelope, but more emphasis should be placed on the energy efficiency requirements of relevant systems. Additionally, the requirement for calculating the dynamic cooling load and heat sources selection was not suitable for UMSs; (3) for alternative items, the characteristics of UMSs included the ability to utilize the heat dissipation from trains and piston wind, as well as relevant EEMs. However, the energy savings and benefits of various measures should be verified in more cases and recommended according to local conditions.

The results of this study identified the difference between the energy use evaluation of UMSs and APBs, summarized the benchmark values of relevant parameters and expanded the existing building EPC framework to make a basis for evaluating the energy performance of UMSs. The results will also help improve the relevant energy-efficient regulations of UMSs and provide a reference for the energy performance evaluation of other public transportation buildings.

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Nomenclature

A	number of passengers	IPLV	Integrated Part Load Value
E	energy consumption (kWh)	LEED	Leadership in Energy and Environmental Design
F	floor area (m^2)	LPD	Lighting Power Density
G	air volume (m^3/h)	PSDs	Platform Screen Doors
h	air enthalpy (kJ/kg)	RESR	Relative Energy-Saving Rate
N	power consumption of equipment (kWh)	SEER	Seasonal Energy Efficiency Ratio
P	electric power (kWh)	UMSs	Underground Metro Stations
Q	cooling load (kW)	WTF	Water Transport Factor
q	total heat dissipation of an adult man (kW)	Subscripts	
Greek symbols		a/b	average time passengers spent in the hall and the platform while getting in/out
τ	time (s)	chw	chilled water
ρ	air density (kg/m^3)	cp	condensate water pump
Abbreviations		cs	cooling system
APBs	Aboveground Public Buildings	ct	cooling tower
ATF	Air Transport Factor	cw	condensate water
COP	Coefficient of Performance	lv	limit value
EER	Energy Efficiency Ratio	L	lighting system
EEMs	Energy-Efficiency Measures	ms	mechanical supply air
EPC	Energy Performance Certification	o	outdoor air
EUI	Energy Use Intensity	s	system
FEI	Fan Energy Index	t	tunnel air
VAC	Ventilation, and Air Conditioning	tia	train-induced air

Appendix A

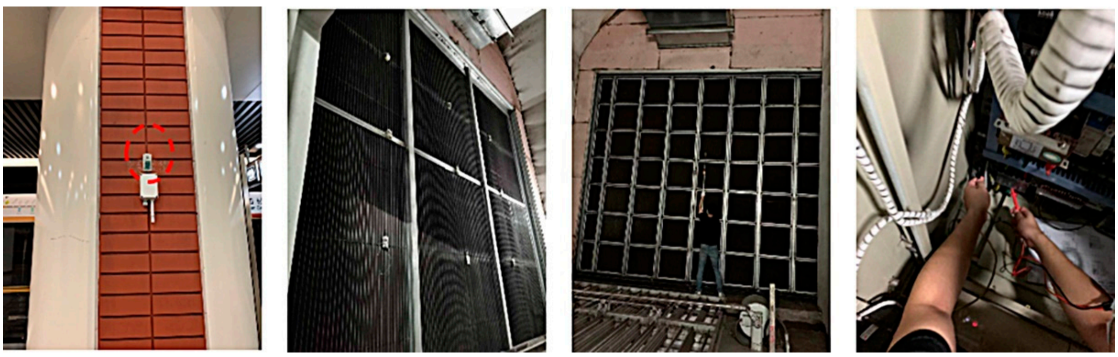

Figure A1. On-site measurement pictures.

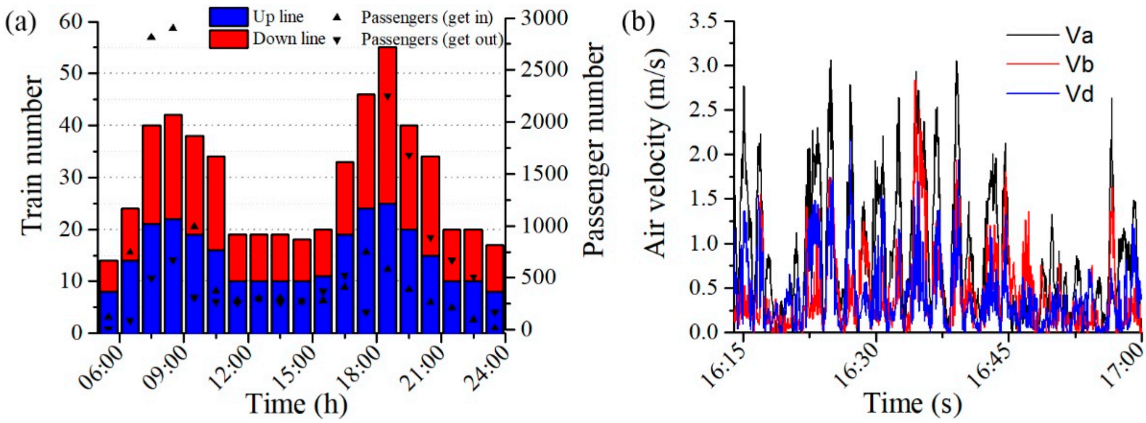

Figure A2. (**a**) Train number and a day's passenger volume at test stations and (**b**) air velocity in different passages.

Table A1. Measuring instrument information.

Measuring Instruments	Interval (s)	Range	Accuracy
HOBO UX100 data logger	10	−20 °C–70 °C 1–95%	±0.21 °C ±2.5%
Testo 175H1	10	−20 °C–55 °C 0–100%	±0.4 °C ±2%
Testo 405i	2	−20 °C–60 °C 0 m/s–30 m/s	±0.5 °C ±(0.1 m/s + 5% of mv) (0 m/s–2 m/s)
TSI 9535	1	−18 °C–93 °C 0 m/s–30 m/s	±0.3 °C ±0.015 m/s (0.15 m/s–30 m/s)
Fluke 568 infrared thermometer	-	−40 °C–800 °C	±1 °C

Table A2. Equations used for energy calculation of the evaluation system.

Equation No.	Equation	References
(A1)	$E_{VACl\nu} = \frac{Q_{VAC}}{EER_{sl\nu}} \times \tau_{VAC}$	[16]
(A2)	$Q_{VAC} = Q_{tia} + Q_{passenger} + Q_{device} + Q_{ms}$	[16]
(A3)	$Q_{tia} = \rho(G_o\Delta h_1 + G_t\Delta h_2)/3600$	[16]
(A4)	$Q_p = q_p\left(N_{hall} + N_{platform}\right)$	[16]
(A5)	$N_{hall} = A_{in}\frac{a_1}{60} + A_{out}\frac{b_1}{60}$	[16]
(A6)	$N_{platform} = A_{in}\frac{a_2}{60} + A_{out}\frac{b_2}{60}$	[16]
(A7)	$Q_d = P_{device}$	[16]
(A8)	$Q_{ms} = \rho G_{ms}\Delta h_1/3600$	[16]
(A9)	$EER_s = \frac{Q_{VAC}}{\sum N_i}$	[63]
(A10)	$\sum N_i = N_{chiller} + N_{cp} + N_{ct} + N_{terminal}$	[63]
(A11)	$EER_{sl\nu} = \frac{1}{\frac{1}{EER_{csl\nu}} + \frac{1}{WTF_{chwl\nu}} + \frac{1}{EER_{terminall\nu}}}$	[63]
(A12)	$EER_{cs} = \frac{Q_{VAC}}{\sum N_j}$	[63]
(A13)	$\sum N_j = N_{chiller} + N_{cp} + N_{ct}$	[63]
(A14)	$EER_{csl\nu} = \frac{1}{\frac{1}{COP_{l\nu}} + \frac{1}{WTF_{cwl\nu}} + 0.02}$	[63]
(A15)	$E_L = \frac{P_L \times F}{1000} \times \tau_L$	[16]

Table A3. Key parameters for calculating Q_{VAC} and E_{vaclv}.

The Parameters	The Values	References
$h_{indoorair}$	55.05 kJ/kg	Measured
h_t	58.05 kJ/kg	Measured
COP_{lv}	5.6	[63]
WTF_{cwlv}	30	[63]
WTF_{chwlv}	The parameter does not exist in this kind of air-conditioning system	-
$EER_{terminallv}$	8	[63]

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